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ANALYSIS OF RADON AND RADON PROGENY IN
RESIDENCES: FACTORS THAT AFFECT THEIR
AMOUNTS AND METHODS OF REDUCTION

THESIS

David R. Little
Captain, USA

AFIT/GNE/ENP/85M-14

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ANALYSIS OF RADON AND RADON PROGENY IN RESIDENCES:

FACTORS THAT AFFECT THEIR AMOUNTS AND METHODS OF REDUCTION

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Nuclear Effects Engineering

David R. Little, B.S.

Captain, U.S. Army

March 1985

Preface

The purpose of this study was to investigate the effectiveness of using an electrostatic precipitator as a means for reducing harmful levels of radon progeny in the home. This is an important study because more and more homes may be experiencing buildup of dangerous levels of radon and radon progeny due to extensive efforts to save energy. By sealing up the homes, air exchange rates are drastically reduced thus causing radon daughter concentrations to build up in the home. During this investigation I will look at a method which may be effective in reducing these dangerous levels.

In preparing for and carrying out the experiments in this thesis I received a great deal of help and guidance from others. I am deeply indebted to my thesis advisor, Dr. George John, for his guidance, knowledge and occasional kick when the need presented itself. I would also like to thank Bob Hendricks for his support and assistance with much of the equipment. A special thanks goes to Carl Shortt and the members of the AFIT fabrication shop for their assistance in building the Radon Test Chamber. Additionally, I would like to thank Dr. Hagee and his associate, Dr. Jenkins, of Monsanto Mound Facility for assistance in calibrating the large Lucas cells used in radon gas measurement. Finally, I want to thank my wife Ann for her untiring support and devotion during those moments when I wondered if it was all worth the effort and pain.

David R. Little

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Abstract

The effectiveness of using an electrostatic precipitator as a means for reducing harmful levels of radon progeny in the home was evaluated. A commercially available precipitator, manufactured by the Honeywell Corporation, was used during the course of this study. The specific model used was the Honeywell Electronic Air Cleaner model number F50A1009.

Daughter concentrations were measured by the modified Tsivoglou method. Samples were collected on a 2-inch millipore filter and alpha emissions were measured with a ZnS(Ag) scintillator. A sample collection time of 5 minutes was used. Sample counting intervals of 2-5, 6-20, and 21-30 minutes after sample collection were used.

During this study air samples were made using the blower fan and filters alone with no power to the electrostatic precipitator, and with the electrostatic precipitator energized. The reduction in the working level as a result of using the blower fans and filters only was 75 percent. With the electrostatic precipitator energized the reduction level rose to 90 percent. It is therefore concluded that the electrostatic precipitator is an effective means for reducing radon progeny concentrations in the home.

ANALYSIS OF RADON AND RADON PROGENY IN RESIDENCES:

FACTORS THAT AFFECT THEIR AMOUNTS AND METHODS OF REDUCTION

I. Introduction

Purpose

The purpose of this thesis was to study and quantify the effective-
ness of using an electrostatic air cleaner in reducing the radon progeny
concentrations in homes.

Background

Inhalation of air containing radioactive radon gas or progeny may
result in an exposure of the respiratory tract to harmful levels of
ionizing radiation. Prolonged exposure to this radiation has been
attributed to a high incidence of lung cancer cases among mine workers
in the United States and Eastern European countries (1:56;7:98). Even
though knowledge of the potential radiation hazard exists, very few
efforts have been directed toward the control and reduction of this
hazard. Efforts to control this hazard are hampered because of the
lack of understanding of the complex relationship between radon, its
progeny, and their environment (23:1.1). It was believed originally
that the lung cancers in mine workers were due to high levels of radon
gas; however, W.F. Bale demonstrated that under all practical circum-
stances the dose to critical tissue in the lung area was due predomi-
nately to the short lived daughters of Ra-222 (Po-218, Pb-214, Bi-214,
and Po-214) which are present in radon laden air, rather than to the
radon gas itself (4:323).

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Not long ago it was believed that the only persons who were exposed to significantly high levels of radon and its daughters were underground mine workers. The concentration of radon gas was expected to be high because of the large quantity of uranium or radium content ores, the large surface area for emanation, and the reduced ventilation (23:1.1). In recent times many articles have been published expressing growing concerns toward the general public's exposure to hazardous levels of ionizing radiation. Initially concerns were directed toward those hazards produced by man (i.e., nuclear power plants, use of nuclear weapons, and medical applications of radiation). More recently though, natural sources of radiation have received increased attention. The most recent articles have been concerned with the magnitude and variation of indoor radon progeny inside residential houses (24;27;32; 33;38). These reports have shown that indoor exposures to radon progeny may be several times greater than that experienced outdoors. These elevated concentrations are usually associated with homes which have been constructed on top of soil with high uranium or radium content, resulting from natural soil formation or through technological enhancement of the natural radiation (23:1.1). Technological enhancement is responsible for elevated indoor radon concentrations in homes built o er reclaimed phosphate mine lands in Florida and in Colorado where uranium mine tailings were used as fillers (9;28). Even though the general populations exposure to radon progeny has been increased by mismanagement of mining wastes, the overwhelming majority of collective dose equivalent to the U.S. public is due to the natural source occurrences of radon and its progeny.

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Typical Ra-222 concentrations in U.S. houses, averaged over a year, are in the range 0.2 - 4.0 pCi/liter (24:278). This value has been estimated to be responsible for lung dose-equivalents that are approximately 5 percent of the occupational limit (23;1.2). The largest contribution to the collective lung dose equivalent is from all natural background radiation.

Prior to the last ten years, before energy conservation measures were instituted in home construction, typical exposures to radon progeny and other indoor pollutants were low. This was due to high infiltration rates usually on the order of 1 to 2.5 air changes per hour. Since that time more people have become extremely energy conscious because of increases in energy costs and federally-sponsored energy-conservation programs. The move toward more energy-efficient homes has led to dramatic reductions in residential air infiltration rates. The Department of Energy estimates that over 50 percent of U.S. home owners have taken action to tighten their houses, and 20-30 percent have an air ventilation rate of less than one air change per hour (23;1.2). The continuation of these trends and the fact that most people will spend 80 percent or more of the day indoors (39:277) will mean an increase in the radon progeny concentration and greater radiation exposure to the general public.

Origin of Radon

Radon-222 gas and its short lived daughters are the intermediate decay products of the naturally-occurring decay series of Uranium-238. The parent radionuclide U-238 which was formed at the earth's creation

is relatively stable with a half-life of 4.5×10^9 years (36:47). Because of its primordial origins U-238 is found in the earth's crustal material in concentrations that can vary greatly with location and geological formation in the region.

The primary radiation exposure from the Uranium decay series begins with the decay of Radium-226. Radon-222, which is the first decay daughter of Ra-226, is an inert noble gas that is capable of exhalating from the air spaces within the soil or other material containing the parent radionuclide. Radon-222 has a half-life of 3.82 days (36:45) and decays into the elements polonium, lead and bismuth. The primary decay scheme for radon is shown in Figure 1. The daughters are also referred to as Ra-A, Ra-B and Ra-C respectively.

Radon exhalation from ground soils is affected by several physical and meteorological factors, besides the soil concentration. The condition of the soil, porosity, the amount of air spaces found between soil constituents, is a major factor in determining the rate at which gas moves through the material. To illustrate, the diffusion, movement of the gas, through sand would be slower than the diffusion found in soil containing large fragments with large interstitial spaces. The moisture content and snow or ice covering on soil will also decrease the emanation rate of the radon gas (23:1.5). The flux (pCi/m^2 * sec) is reduced by slowing down the linear diffusion rate which causes more of the gas to decay before it escapes into the free air space above the ground. Because the radon progeny are metal atoms they, the progeny, will then remain trapped in the medium. Drastic changes in the flux may come about as a result of sudden transient changes in barometric pressures

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           Radionuclide          Half-life

    222    RADON                  3.82 days
                                  α - 5.49 Mev
              │
              ▼
    218    POLONIUM               3.05 minutes
                                  α - 6.0 Mev
              │
              ▼
    214    LEAD                   26.8 minutes
                                  B
              │
              ▼
    214    BISMUTH                19.6 minutes
                                  B
              │
              ▼
    214    POLONIUM               164 μSec
                                  α - 7.69 Mev
              │
              ▼
    210    LEAD                   Stable


              ━━━━━━▶ Indicates Alpha Decay
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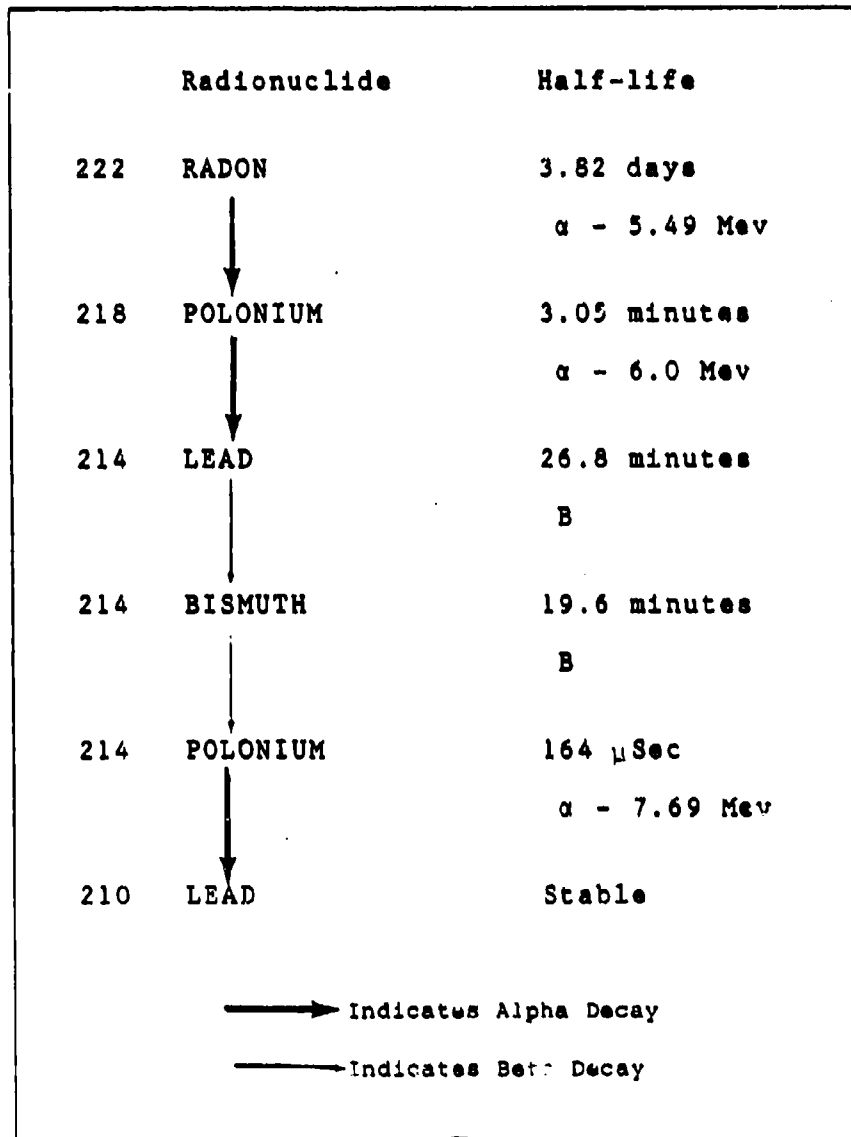
Figure 1:   Primary Decay Scheme for Radon Gas

above the soil-air interface (17:216). A drop in barometric pressure
reduces the pressure on gas emanation and exhalation rates can increase.
Under this condition radon gas concentrations could be several orders
or magnitude above that predicted for simple diffusion (23:1.5). In
contrast as the barometric pressure increases a corresponding decrease
in radon gas flux could result.

Other factors such as temperature and winds between the ground and
open air can influence the flux; however, these factors are of lesser
importance because they may occur over a short period of time.

Sources of Indoor Concentrations

Radon gas exhalation into a reduced dilution volume will cause an
increase in steady state concentrations of the gas. This is usually
the situation when homes are constructed on top of soil containing
radium precursors and ventilation rate of the house is reduced. The
house foundation may create a barrier to radon gas diffusion causing
more of the gas to decay before it moves out of the floor or medium.
Radon has been reported as having a relaxation length of approximately
8 cm (5:269); because of this, large length radon gas easily enters
into the home. The soil beneath homes is generally accepted as the pri-
mary source of radon entry. However, several other access pathways have
been found to be important sources of radon.

Construction Materials

Construction materials which contain high levels of radium or
uranium contents have been studied and reported to contribute to the
indoor concentrations of radon gas (15;18;30). These studies have

found that materials such as concrete, cement blocks, gypsum board, and masonry contain radioactive material which contribute to the source of radon gas in buildings. Concrete made from beach sands and mixtures of granite, pumice, and alum shale have among the highest reported radon exhalation rates (26:307). Another source of high radium content in building materials is the use of residues from industrial processes. A large contributor is the use of Phosphogypsum, a calcium sulfate produced by treatment of phosphate ores with sulfuric acid. This material is generally used in wallboard. In this treatment Ra-226 usually follows the calcium, leading to tens of pCi/g in the gypsum (26:308). The U.S. is the largest producer of the phosphate rock material, but use of the phosphogypsum is found in other countries having little natural gypsum. The principal use of a byproduct material in the U.S. is concrete blocks using phosphate slag, which contains much of the Ra-226 and U-238 in the phosphate ore. These blocks have been estimated to have Ra-226 concentrations of about 20 pCi/g (26:308).

Radon in Water

Radon gas is soluble in water, but the solubility decreases with an increase in temperature. Ground waters which are encased in radium bearing rock formations can have concentrations of Rn-222 greater than 50,000 pCi/l (25:311). The radon gas can quickly transfer to the air when heated or when aerated as in a shower, a faucet aerator, or appliance. Several homes in Maine, out of 2000 surveyed, were found to have indoor concentrations of radon gas in excess of 10 pCi/l, with the primary source of the radon being the potable water (12:344).

Natural Gas

As with water, deposits of natural gas located in or near soil formations which have high content of radium can also become a source of radon gas in homes. Radon diffuses from the rock into the well and infiltrates the gas. Release into the home occurs when the natural gas is used for cooking. The concentration of radon gas in gas distribution lines in the U.S. has been found to range from 1 to 100 pCi/l (26:312). Differences in storage and transmission times will alter the radon concentration delivered to the home.

Indoor Concentrations of Radon and Progeny

Once radon gas has entered the home it will mix with the room air and decay according to the scheme shown in Figure 1. The daughter products consist of heavy metals atoms of polonium, lead and bismuth. Each is radioactive and possesses a short half-life less than 30 minutes. These decay products attach themselves to dust particles and other aerosols in the room air. Depending on the dust concentration in the room, some of the daughter products will remain unattached, positively charged ions and as such may attach themselves to other small polar molecules like water vapor.

Effect of Ventilation. Many homes are not airtight and therefore outside air will infiltrate through doors, cracks, and windows. This rate is governed by several factors, i.e., wind speeds, temperature, and pressure differences between inside and outside air. The rate of infiltration air into the home has a great bearing on the radon gas concentration in the home. In a home with a volume, V, room air that

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seeps outdoors at a rate F (volume/time) must be replaced by an equal volume of outside air. The airborne activity removed during a time unit per unit volume is then F/V * (C(in) - C(out)), where C(in) and C(out) are the indoor and outdoor concentrations. Therefore F/V is the removal rate constant or room infiltration rate. If the outdoor concentration is much smaller than the indoor concentration then the removal rate becomes F/V * C(in) (23:1.9), which implies that as the infiltration rate increases, the radon concentration will be reduced by the factor F/V.

Working Level

In assessing the possible insult to the lungs due to inhalation of radon progeny, a unit known as the Working Level (WL) was defined. This is the link between progeny concentration and the eventual alpha energy imparted to the lungs per volume of air. One Working Level is defined as any combination of Ra-A, Ra-B, Ra-C, and Ra-C' atoms/liter of air that upon decay will release 1.3×10^5 MeV of alpha energy. The Working Level in a room containing radon decay products is determined as:

$$WL = 1.3 \times 10^{-3}C_1 + 5.07 \times 10^{-3}C_2 + 3.73 \times 10^{-3}C_3 \qquad (23:1.13)$$

where C_1, C_2, and C_3 are the concentrations of each daughter in Pci/l

The potential alpha energy in MeV imparted to the lung can be calculated from:

$$PAE(MeV) = 1.3 \times 10^5 \times WL \qquad (23:1.13)$$

A 100 microcurie source of radon in equilibrium with its daughters will give one working level of energy.

Effects of Air Treatment Devices

Control or reduction of radon and radon progeny in residences can be grouped into three broad categories. The first of these is to restrict the movement of radon gas into the home. Second is to provide dilution of the radon gas concentration by increased air ventilation. The third category is removal of progeny through the use of air treatment devices which in addition remove other harmful air pollutants. There are several types of devices which can be used in the control of radon progeny and indoor pollutants. These include the electrostatic precipitator, high efficiency filter, and ceiling fan. Reduction in radon working levels using such devices has been investigated by several investigators (2;13;14). Another method useful in the removal of radon progeny that is receiving renewed interest is the use of ion generators.

Scope

Starting with a steady-state concentration of radon progeny, the effectiveness of an electrostatic precipitator is evaluated. The modified Tsivoglou method is used for analysis. Only limited controls on humidity and temperature were available; therefore, extensive investigation as to their contributions to the changes in concentration levels were not measured.

General Approach

The approach to this investigation included 1) the preparation of an experimental chamber for obtaining a steady-state source of radon gas and radon progeny, 2) refinement and verification of a method for sampling and analyzing radon progeny, 3) collecting of radon progeny

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under varying conditions, e.g., with and without air treatment devices,

4) analysis of results under varying conditions to determine effective-

ness of air treatment device.

Sequence of the Report

Chapter II contains the basic theory and math analysis used in
this thesis. Chapter III explains the radon gas generator and test
chamber. Chapter IV contains the details of the measurement methodology
omployed and the equipment used for the experiments.. Chapter V contains
a review of the data and results. Chapter VI contains the conclusions
drawn from the results obtained in the experiment phase. In addition
Chapter VI contains a list of recommendations for improvements and
further studies.

II. Theory and Analysis

Introduction

The decay products of radon gas are formed as positively charged atoms. These atoms readily attach themselves to aerosols and dust particles suspended in ambient house air. When air is drawn through an air sampling device the attached and unattached daughters are deposited onto a filter. The filters are then analysed by using a technique known as gross alpha counting.

The concentrations of the short-lived progeny of radon attached to dust particles in air is measured by taking three integral counts of alpha activity collected on the filter. In a technique first developed by E.C. Tsivoglou (35:40) and later modified by J.W. Thomas (34), the concentrations of Ra-A, Ra-B, and Ra-C in air are calculated from three integral counts of the combined alpha particle activity of Ra-A and Ra-C. In this thesis post sample count intervals of 2-5, 6-20 and 21-30 minutes were used. This method is used because it has an inherent advantage in that a simple counter can be used to record activity, as described later in Chapter 3.

In using the modified Tsivoglou method the following assumptions were made: 1) only radon progeny are responsible for alpha activity detected on filter, 2) counter efficiency is the same for all radionuclides, 3) concentrations of radon progeny remains the same during sample collection.

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Math Methodology

The development of the analysis used for calculating the progeny concentrations is accomplished in essentially two steps. The first is to solve three interrelated linear differential equations which relate the number of atoms for each decay product deposited on a filter to the airborne radionuclide atom concentration.

The set of differential equations which describe the rate at which radon progeny atoms are deposited on the filter is:

Change in number of atoms = Production - Decay

$$\frac{dn_i(t)}{dt} = q_i v + \lambda_{i-1} n_{i-1}(t) - \lambda_i n_i(t) \tag{1}$$

where i = 1 for Ra-A
         2 for Ra-B
         3 for Ra-C

n_i = number of the ith type of atom on the filter

λ_i = decay constant of the ith type of atom (min^{-1})

q_i = air concentration of the ith type atom (atom/liter)

v = air sampling rate (liter/min)

The equations are then of the form:

$$\frac{dy}{dx} + ay = f(x) \tag{2}$$

with a general solution:

$$y = e^{-ax} \left[Y_0 + \int f(x) e^{ax} dx \right] \tag{3}$$

where Y_0 is a constant of integration. In the solution the constants of integrations are evaluated using the initial condition that each

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$n_i^o(t)$ is equal to zero at the start of the sampling interval, i.e., $n_i^o(t) = 0$ at $t = 0$. In a sampling time of t_s the number of radon progeny deposited on the filter are:

$$n_1^o(t_s) = q_1 v \left(\frac{1 - e^{-\lambda_1 t_s}}{\lambda_1} \right) \tag{4}$$

$$n_2^o(t_s) = q_1 v \left[\frac{1 - e^{-\lambda_2 t_s}}{\lambda_2} + \frac{e^{-\lambda_2 t_s} - e^{-\lambda_1 t_s}}{\lambda_2 - \lambda_1} \right]$$
$$+ q_2 v \left[\frac{1 - e^{-\lambda_2 t_s}}{\lambda_2} \right] \tag{5}$$

$$n_3^o(t_s) = q_1 v \left[\frac{1 - e^{-\lambda_3 t_s}}{\lambda_3} + \frac{e^{-\lambda_3 t_s} - e^{-\lambda_2 t_s}}{\lambda_3 - \lambda_2} - \frac{2 e^{-\lambda_3 t_s}}{(\lambda_3 - \lambda_2)(\lambda_3 - \lambda_1)} \right.$$

$$\left. + \frac{2 e^{-\lambda_2 t_s}}{(\lambda_3 - \lambda_2)(\lambda_2 - \lambda_1)} - \frac{2 e^{-\lambda_1 t_s}}{(\lambda_3 - \lambda_1)(\lambda_2 - \lambda_1)} \right] + q_2 v \left[\frac{1 - e^{-\lambda_3 t_s}}{\lambda_3} \right.$$

$$\left. + \frac{e^{-\lambda_3 t_s} - e^{-\lambda_2 t_s}}{\lambda_3 - \lambda_2} \right] + q_3 v \left[\frac{1 - e^{-\lambda_3 t_s}}{\lambda_3} \right] \tag{6}$$

Equations (4), (5), (6) can be written in matrix form as

$$\begin{vmatrix} n_1^o \\ n_2^o \\ n_3^o \end{vmatrix} = v \begin{vmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{vmatrix} \begin{vmatrix} q_1 \\ q_2 \\ q_3 \end{vmatrix} \tag{7}$$

or

$$N^o = vKQ \tag{8}$$

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where capital letters in equation (8) denote the matrices in equation (7). The elements of the matrix K are given in Appendix A.

The second step in solving for the airborne concentration is to relate the expected Ra-A and Ra-C alpha disintegrations over the three counting intervals to the number of atoms of each radionuclide present on the filter at the end of sample collection. The linear differential equations which describe this relationship are also of the form in equation (2), with a solution of the form denoted in equation (3). In evaluating the constants of integration, the time t is taken as 0 at the end of sample collection, and the number of atoms on the filter at start of counting time, $n_i(t)$, is set equal to the number of atoms on the filter at the end of sample collection, i.e., $n_i(t_s) = n_i(t)$ at t = 0 . At a time t, measured from start of counting, the number of each type of radon progeny atom on the filter is given by the relationships:

$$n_1(t) = n_1^o(t_s)\, e^{-\lambda_1 t} \tag{9}$$

$$n_2(t) = n_1^o(t_s) \left[\frac{\lambda_1 e^{-\lambda_1 t}}{(\lambda_2 - \lambda_1)} - \frac{\lambda_1 e^{-\lambda_2 t}}{(\lambda_2 - \lambda_1)} \right] + n_2^o(t_s)\, e^{-\lambda_2 t} \tag{10}$$

$$n_3(t_s) = n_1^o(t_s) \left[\frac{\lambda_1 \lambda_2 e^{-\lambda_1 t}}{(\lambda_3 - \lambda_1)(\lambda_2 - \lambda_1)} - \frac{\lambda_1 \lambda_2 e^{-\lambda_2 t}}{(\lambda_3 - \lambda_2)(\lambda_2 - \lambda_1)} \right.$$

$$\left. + \frac{\lambda_1 \lambda_2 e^{-\lambda_3 t}}{(\lambda_3 - \lambda_2)(\lambda_3 - \lambda_1)} \right] + n_2^o(t_s) \left[\frac{\lambda_2 e^{-\lambda_2 t}}{\lambda_3 - \lambda_2} - \frac{\lambda_2 e^{-\lambda_3 t}}{\lambda_3 - \lambda_2} \right] + n_3^o(t) e^{-\lambda_3 t}$$

$$\tag{11}$$

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Taking equations (9) and (11) and integrating over the counting intervals for each of the three integral count times, one obtains total count of alpha particle activity on the filter at the end of sample collection. The relationship is given by the equation:

$$c_j(t_i) = \epsilon \left[\sum_i \int_{t_1}^{t_2} \lambda_i n_i(t)\, dt \right] \tag{12}$$

where ϵ = product of the detector and filter paper efficiencies

The gross counts observed in the detector over the time intervals are related to the expected number of disintegrations from both alpha emitters. Substituting equations (9) and (11) into (12), and performing the indicated integration results in an equation of the form:

$$c_j(t) = \epsilon \left[1_{j1}(t_j)\, n_1^0(t_s) + 1_{j2}(t_j)\, n_2^0(t_s) + 1_{j3}(t_j)\, n_3^0(t_s) \right] \tag{13}$$

The total counts of the alpha particle activity on the filter is then related to the number of radon progeny atoms deposited on the filter at the end of sample collection given in matrix form:

$$\begin{vmatrix} n_1 \\ n_2 \\ n_3 \end{vmatrix} = \epsilon \begin{vmatrix} 1_{11} & 1_{12} & 1_{13} \\ 1_{21} & 1_{22} & 1_{23} \\ 1_{31} & 1_{32} & 1_{33} \end{vmatrix} \begin{vmatrix} n_1^0 \\ n_2^0 \\ n_3^0 \end{vmatrix} \tag{14}$$

$$N = \epsilon L N^0 \tag{15}$$

The matrix elements for L are given in Appendix A. Combining equations (8) and (15), one obtains the matrix relationship:

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$$N = \epsilon LVKQ \qquad (16)$$

The solution of equation (16) for Q, the concentration matrix, results in the matrix equation:

$$Q = \frac{1}{\epsilon V} K^{-1}L^{-1}N = \frac{1}{\epsilon V} MN \qquad (17)$$

This yields a set of equations relating the three integral counts of activity on the filter to the air concentration of each daughter. The equations are:

$$q_1 = \frac{1}{\epsilon V}\left[m_{11}(t_s,t_1)\ n_1 + m_{12}(t_s,t_2)\ n_2 + m_{13}(t_s,t_3)\ n_3 \right] \qquad (18)$$

$$q_2 = \frac{1}{\epsilon V}\left[m_{21}(t_s,t_1)\ n_1 + m_{22}(t_s,t_2)\ n_2 + m_{23}(t_s,t_3)\ n_3 \right] \qquad (19)$$

$$q_3 = \frac{1}{\epsilon V}\left[m_{31}(t_s,t_1)\ n_1 + m_{32}(t_s,t_2)\ n_2 + m_{33}(t_s,t_3)\ n_3 \right] \qquad (20)$$

where m_{ji} are elements of the matrix M derived by multiplying the inverse of matrix K with the inverse of matrix L.

Analysis of Error

In any experiment there is introduced in the final result a certain degree of error or uncertainty. These uncertainties can be attributed to either systematic or random errors in the experiment. In measuring the airborne concentrations of radon daughters, errors are introduced by the statistical fluctuations in the decay process, uncertainty in the regulation of air flow, and the efficiency of the collection/detection

system. The extent of uncertainty in the radionuclide atom concentration was calculated through application of the standard error propagation formula (20:131). This technique assumes that the counts of the radionuclides in each counting interval are independent of each other. The error analysis here includes the contribution from the gross counts in each of the three time intervals, assuming a Poisson distributed counting error. The uncertainty in the air flow rate and detector efficiency is also evaluated. The error of the calculated concentration of the radon progeny is then estimated by the equation (19:12):

$$Sq_i^2 = \frac{1}{(\varepsilon v)^2} \left[\sum_{j=1}^{3} m_{ij}^2 s_{cj}^2 + \left(\sum_{j=1}^{3} m_{ij}^2 \ C_j^2 \right) \cdot \left(\frac{s_v^2}{v^2} + \frac{s_g^2}{g^2} \right) \right]$$

(21)

where Sq_i = uncertainty in calculated concentration with i = 1 for Ra-A, 2 for Ra-B, 3 for Ra-C

S_{cj} = statistical uncertainty of one standard deviation in counts for each radionuclide with j = 1, 2, 3

S_v = systematic error in air sample rate

S_g = systematic error in detection efficiency of counter

The systematic uncertainties in the air sample rate and detector efficiency were calculated to be 4.5 and 4.9 percent respectively.

Weighted Least Square Method

A weighted least squares regression analysis for calculating the radon progeny concentrations of each radionuclide deposited on a filter by an air sampling device was developed jointly by Dr. D. Shankland and

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III. Radon Gas Test Chamber

Introduction

The experiments conducted during the course of this investigation were conducted in the control room for the Hot Cell of building 470 Area B, Wright-Patterson AFB, Ohio. Previous air samples collected in the Hot Cell showed concentration levels of radon progeny to be in the ranges of 0.18-0.25, 0.16-0.2, 0.10-0.15 pCi per liter for Ra-A, Ra-B, and Ra-C respectively (21:8a). These levels were too low to effectively measure any reductions or changes in concentrations as a result of using air treatment devices; therefore, it was necessary to increase the radon and radon daughter concentrations by artificial means. The purpose of this chapter is to describe the method and equipment used to enhance the radon gas concentration. Specific areas to be discussed are:

1) Physical Description of Room

2) Production and Distribution of Radon Gas

3) Environmental Control

Physical Description

The radon gas test chamber was set up using a procedure similar to that described by S.N. Rudnik (29:464). The room selected was the personnel changing and service room of the Hot Cell in Bldg. 470. The physical dimensions are shown in Figure 2.

The volume of the room was calculated to be 99 m^3. The room had two shower stalls and two toilet stools, with all inlet water lines sealed. This room was not typical of most living areas found in U.S.

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Dr. G. John (30). The analysis program was developed to calculate the airborne concentrations of each of the daughter products and will be compared with the results calculated using the modified Tsivoglou method. A comparison of the daughter concentrations is included in Appendix E.
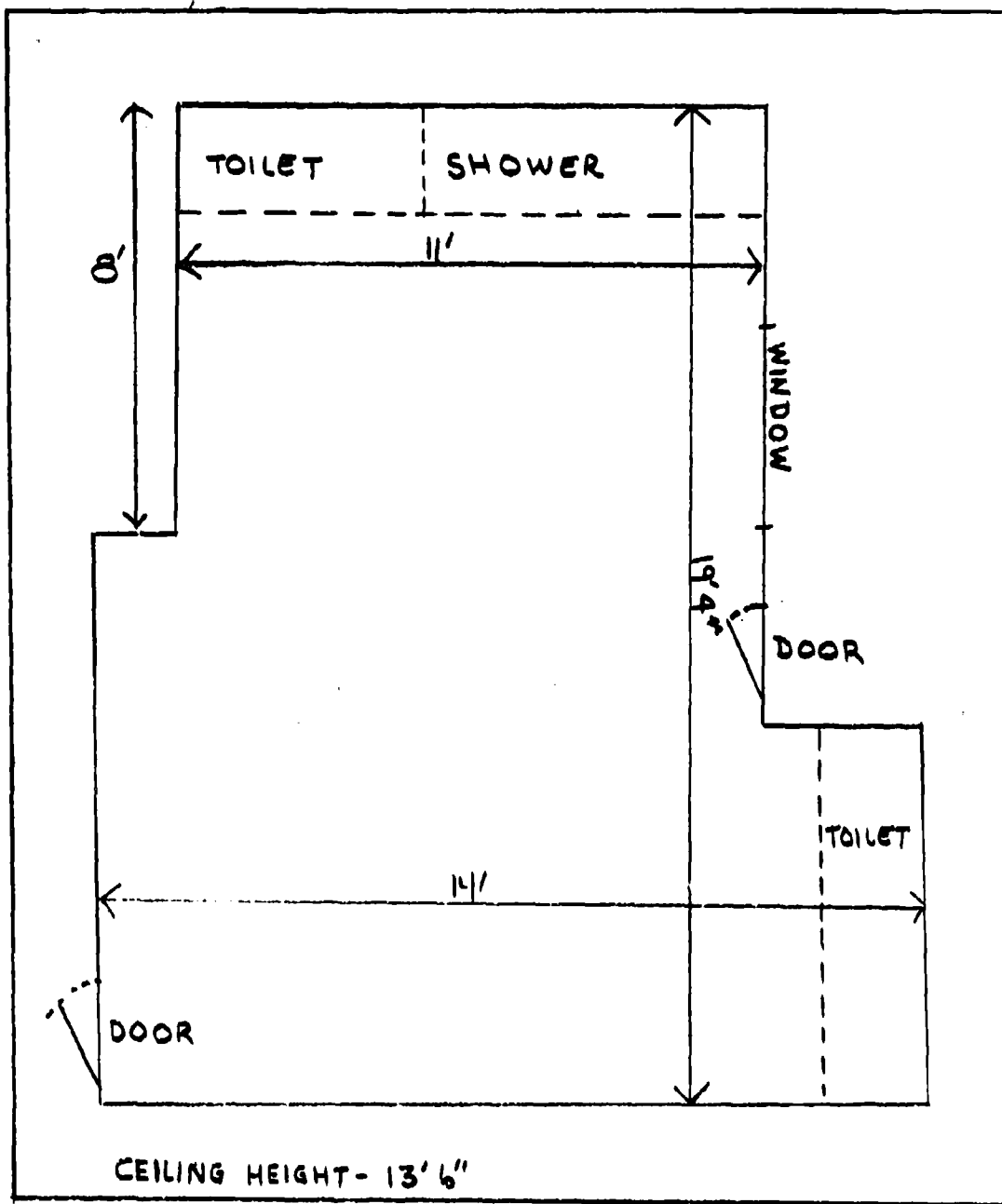
Figure 2. Physical Dimensions of Radon Test Chamber

homes. It was, however, determined that tighter environmental controls could be maintained as compared to other available rooms in the building. The walls were painted cinder block and the floor was a solid concrete slab. Physical modifications of the room were made to accommodate the equipment required to enhance the radon gas concentration. The major modifications included the drilling of holes in the wall, for the purpose of routing necessary air and power cables to the equipment, and installation of an exhaust duct to control the air infiltration rate into the room.

Radon Gas Production and Distribution

Radon-222 gas was generated from a 100 microcurie source of Ra-226. The radium solution was made by mixing a 100 microgram liquid source with a 1 molar solution of nitric acid. The 1 molar acid solution was made by mixing 65 ml of 1.42 molar solution of nitric acid with 1 liter of deionized water. Ambient air, supplied from a 60 lb air source was routed through a water separator and regulator. The air supply branched off into two routes. The first carried air through the radon gas system and the other fed directly into the gas manifold providing make-up (dilution) air. The air supply lines for both radon gas generation and dilution air are shown in Figure 3.

The air supply flow rate was measured using a Roger Gilmont Flow-meter, size 2, serial number B707. The flow of air through the radon gas was maintained at 0.2 1/min. The air was passed through 3 humidifiers before bubbling through the radium solution. The humidifiers were made of 1000 ml flasks filled with approximately 500 ml of water. The
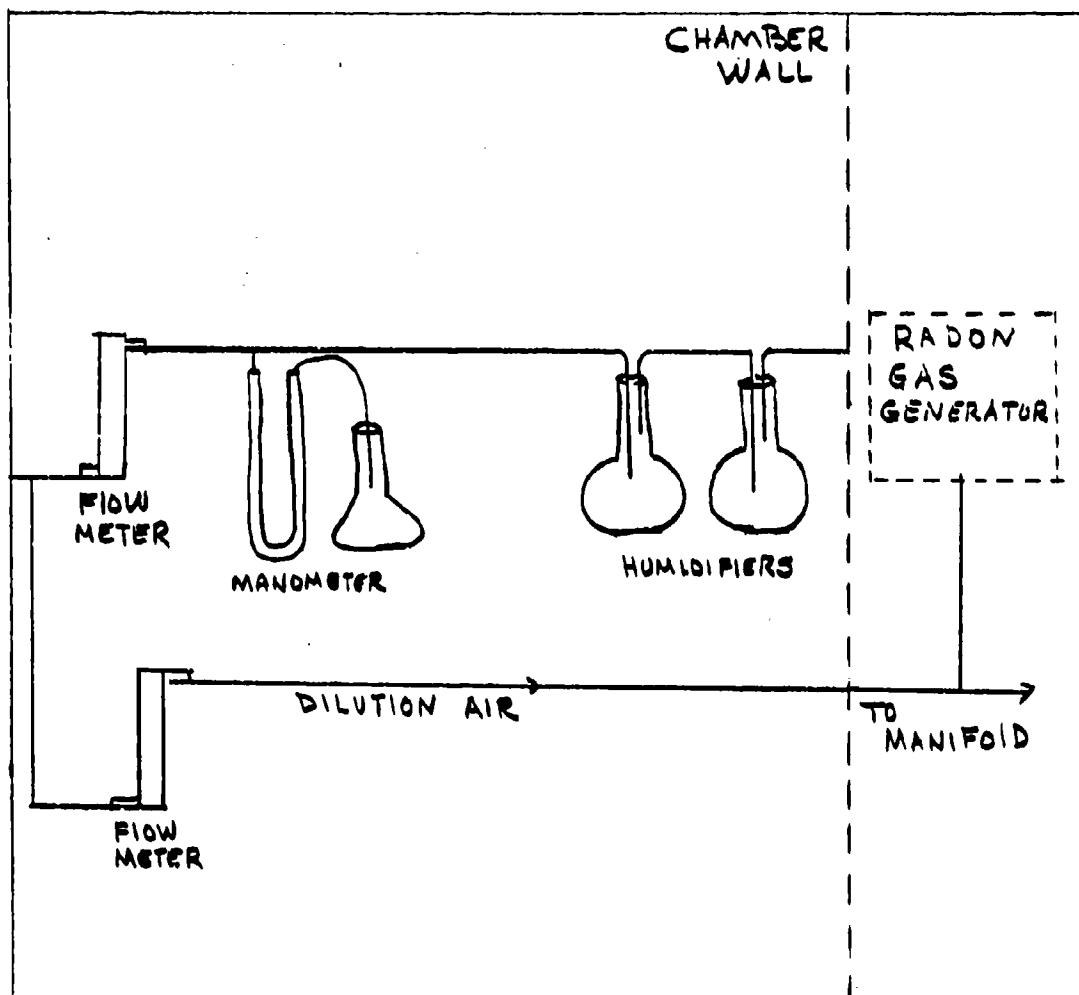
Figure 3. Air Lines for Radon Gas Generator and Dilution Air

pre-humidified air then passed through the radon generator. The radon

gas generator was set up in a metal container which was fixed with a

clear plexiglass top (Figure 4). The metal container was used to con-

tain the radium solution in the event of an accident. Two holes were

drilled into the container 180 degrees apart; one of these was used to
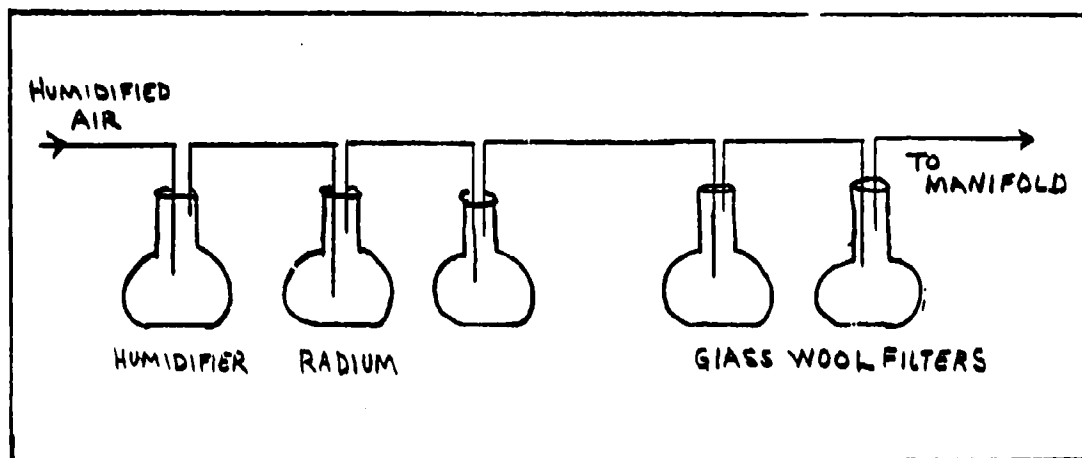
Figure 4. Radon Gas Generator

introduce pre-humidified air to the generator and the other used to trans-
port the radon gas to the distribution system. In the radon generator
the humidified air flowed through a final humidifier, through a flask
containing the radium solution, through a liquid carry-over trap, and
two glass-wool-filled flasks. The radon gas was then transported to the
manifold distribution system on the floor. Prehumidification of the air
was done to prevent the radium solution from drying and contaminating
the gas system with radium residue.

The manifold system shown in Figure 5 was constructed from 3.71 cm
OD poly-vinyl chloride piping. Holes with 0.8 mm diameter were drilled
in the pipe at 60 cm intervals. The pipes were placed on top of 0.5
inch wooden spacers with the holes facing down toward the floor. The
relative size of the hole to the diameter of the pipe insured a more even
distribution of gas into the room.
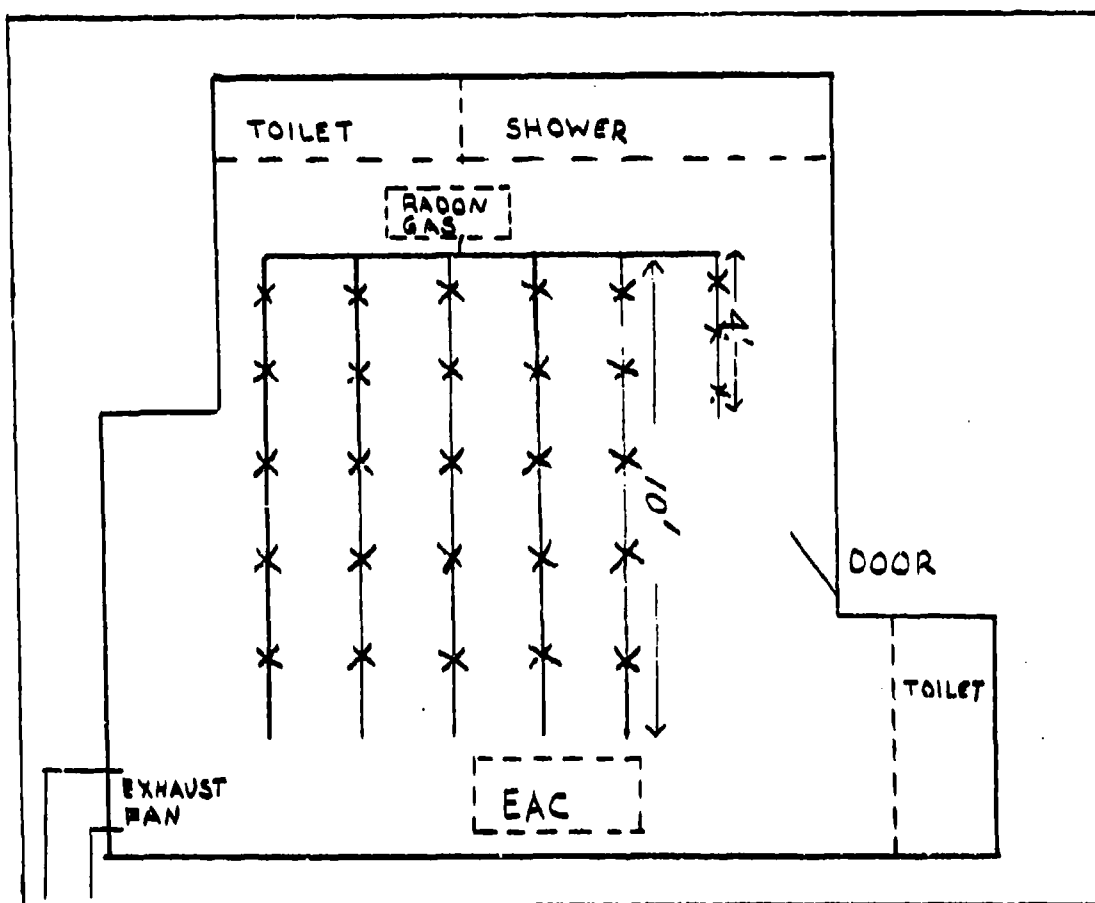
Figure 5. Gas Manifold Distribution System
and Ventilation Exhaust Duct

Roughly 5 liter/min of dilution air was added directly to the mani-
fold. The flow rate was monitored by use of a Roger Gilmont Flowmeter,
size 3, serial number F-116. A U-tube Mercury filled manometer was
placed in series with the radon gas feed line. The primary purpose of
the manometer was to monitor any blockage or restriction of the air flow
through the gas generator.

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The radon gas concentration was monitored using a 3-liter Lucas cell (8:8-10) modified for continuous air flow. The cell was set up in the middle of the room, with the inlet approximately 2 meters above the floor.

Environmental Control

For a steady rate of radon gas emanation, the indoor concentration is highly dependent on the air ventilation rate. Air infiltration, the uncontrolled leakage of air through cracks and gaps in the building, is a dominant mechanism for ventilating houses. In conventional homes infiltration rates vary from 0.5 to 1.5 air changes per hour (24:278). The relation for radon gas to ventilation is given by the following equation:

$$ C \left(\frac{pCi}{l}\right) = C_o \left(\frac{pCi}{l}\right) + \frac{e \left(\frac{pCi}{m^2-h}\right) \times S \left(\frac{m^2}{surface}\right) \times 10^{-3}\left(m^3/l\right)}{V(m^3) \times \left[\lambda_v (ACH) + \lambda_D \left(\frac{decay}{const}\right)\right]} $$

(22)

where C_o = concentration in exchange air from outside

e = emanation rate from walls and floors
S = area of surfaces which emanate radon
V = volume of room
λ_v = air exchange rate
λ_D = decay constant

As can be seen from the equation, the concentration of radon gas is inversely proportional to the air ventilation rate. Because of the critical dependence upon the air infiltration, all doors, cracks, and holes were sealed. Additionally, all existing air conditioning and heating vents were sealed. To insure that a steady state concentration

TABLE I

Air Exhaust Rates as Function of Damper Position

Damper Position	Exhaust Rate (ACH)		
	Condition 1	Condition 2	Condition 3
0.0	0.06	0.05	0.07
0.5	0.43	0.39	0.36
1.0	0.78	0.76	0.76
1.5	1.13	1.17	1.07
2.0	1.47	1.43	1.38
2.5	1.69	1.71	1.65
3.0	1.88	1.88	1.79
3.5	2.04	2.07	2.02
4.0	2.19	2.27	2.30
5.0	2.48	2.66	2.63

of radon gas is maintained at all times, it was imperative that air infil-
tration rates be tightly controlled. To control the air exchange rate in
the room, an exhaust fan was installed approximately 15 cm above and
centered over the entry door, as can be seen in Figure 5. The fan drew
air from the room and exhausted it to the outside. Since there was no
air blowing into the room, make up air had to seep into the room through
the walls and available spaces around the door. The air exhaust rate
from the room through the exhaust duct was measured using an Anemeotherm
serial numbered 7602. The Anemeotherm was provided by the Base Health
Physics section. The measurements were made in the duct between the
chamber wall and the exhaust fan. The air exchange rate could be varied
from 0.06 to 2.48 air changes per hour.

The complete air exchange rates measured are listed in Table I.
The measurements were made under three different conditions. Condition 1

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was without the blower on the electrostatic precipitator in operation. The other two were with the blower operating at low speed and high speed. As can be seen from the figures in Table I, not much difference in the flow rate was introduced by the blower. The damper position is a measure of how far the sliding door was opened (in inches).

IV.   Measurement Methods and Equipment

Introduction

This chapter contains a detailed description of the method and equipment used during the course of the experimental phase of this study.   The areas discussed are:

1) Radon Gas Concentration

2) Radon Progeny Concentration

3) Radon Progeny Removal Device Investigated

The information provided contains the experimental procedure used to obtain the data collected, and the analysis technique used to obtain the reported results.   Thus the intent of this chapter is to provide sufficient detail of the measurement methods so that any student may be able to repeat the experiment.

Radon Gas Concentration

The steady-state concentration of the radon gas must be accurately and precisely known at all times since it is the parent element in the decay series.   Any statistical variation in the concentration will directly add to the error in the radon progeny which already has error associated with counting statistics.

Sampling Method.   To monitor the radon gas concentration within the test chamber, three separate but similar methods were used: 1) Continuous monitor using 3.77 liter Lucas Cell (8:10-18;22), 2) Grab air sample using 3.77 liter Lucas Cell, 3) Air sample using a Radon Collection and Transfer System (RCTS) with small Lucas Cell.

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Continuous Monitor. In the continuous monitor method a large Lucas cell was placed in a light tight canister. The Lucas cell was placed directly onto a 4 inch photomultiplier tube, which was connected to a set of counting and recording equipment. A continuous flow of air through the Lucas cell was accomplished by connecting the Lucas cell to a vacuum line, which was vented above the roof line of the building. A 1/2 inch opening located on the top of the cell provided an inlet for the air. To insure only air containing radon gas was entering the cell, a paper filter was placed over the inlet to trap any radon progeny and dust aerosols. The air was drawn through the cell at a rate of 3 liters/min. The air flow was measured using a size 3 Roger Gilmont flowmeter.

The activity of the radon was then established by the following process. As the radon gas decays within the Lucas cell the alpha emissions cause light scintillations when they interacted with the ZnS(Ag) coating. The light from these scintillations are detected by a photomultiplier tube to produce a pulse that is registered as a count by the counting equipment. The counts were recorded for a 1000 second interval and the total for the interval was printed out automatically on a teletype. The number of counts detected was then used to calculate the radon gas concentration in the test chamber using an integrated count method developed by Jonassen (17:350). This method does not require that the daughter and parent radionuclides be in equilibrium to calculate the concentration of the parent radionuclide. With the fast flowrate as compared to the half-life of the daughter products, equilibrium would not be achieved in the 1000 second count period. The efficiency of the Lucas cell is 0.28 as was determined from data collected by Grosner (8:12-16). Calculation of the efficiency is in Appendix L.

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Grab Sample with Lucas Cell. A second method of sampling and
monitoring the radon gas concentrations in the test chamber involved
using another large Lucas cell. The procedures used with the grab sample
were quite simple. First the Lucas cell is evacuated with a vacuum pump
to as low a pressure as possible, usually 200 microns. The evacuated
cell is then taken to the test chamber, a filter was placed over the
inlet valve, again to insure only radon gas enters the cell. The inlet
is placed through a 50 mm sample port in the access door to the test
chamber. The inlet valve is then opened allowing the radon gas to enter
the cell. It is critical that the time of sample collection be recorded
as this will be needed to calculate the gas concentration. The cell is
then placed in a light tight canister, atop a photomultiplier tube, set
up similar to the continuous monitor. The counts are then recorded for
1000-second intervals. The samples were usually counted for a period of
3-4 hours. Again, using the integrated count method the gas concentra-
tion can be determined.

Radon Collection and Transfer System (RCTS). The third method
of determining the radon gas concentration was used as a verification to
the two large Lucas cell values. The method incorporated the use of the
RCTS. The basic idea of the system is to first collect a sample of air
from the test chamber in an evacuated tank. The air is then sent through
a series of traps to remove the water vapor, carbon dioxide, and finally
through a charcoal filter cooled with dry ice and alcohol where the radon
gas is collected. Once the radon gas has been separated, the charcoal
is heated and helium is used to transfer the radon released to a Lucas

cell. The Lucas cell is then placed on top of a 50 mm photomultiplier tube. The counts are then recorded every 1000 seconds. These counts are then used to calculate the initial gas concentration. A more detailed step-by-step process for the RCTS is in Appendix C. A computer program which uses the integrated count method to determine the gas concentrations is listed in Appendix D.

Environmental Air Samples. During the course of this study measurements of radon gas were made using the equipment and methods described above. The measurements were made in an attempt to insure that no significant amounts of radon gas were introduced into the atmosphere or the inhabited shop areas in and around building 470. Measurements before and after release of radon gas were taken at various locations.

Radon Progeny Concentration

Sampling Method. Radon progeny concentration in the test chamber are made from samples collected through a sample port in the access door leading into the chamber. The sample port was simply a 50 mm hole cut into the plexiglass window in the door. The hole was sealed with air conditioning duct tape to prevent air from entering the room. Radon progeny samples were deposited onto a 50 mm diameter membrane millipore filter using a Gelman air sampler. The air sampler had an average air flow rate of 22 ± 1 liter/min. The millipore filter has essentially a 100 percent collection efficiency for attached and unattached daughters, and is believed not to contribute significantly to burial losses of alpha emissions. A five minute sample time was used for all samples collected during this thesis.

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Counting Instrumentation. Alpha emissions of Ra-A and Ra-C were detected by alpha scintillation methods. A four inch photomultiplier tube was inverted and placed on top of a ZnS(Ag) phosphor disc. This apparatus was then placed in a light tight housing over a sliding tray. The exposed filter paper was placed on this tray. The collecting side of the filter was then moved into position in direct contact with the ZnS(Ag) phosphor coating. As the daughters decayed the alpha emission caused scintillations which were detected by the photomultiplier tube and processed through the detection and counting equipment. The photomultiplier tube was operated at 950 volts.

The efficiency of the system was determined using a 22 mm diameter RaD+E disc standard, and was found to be $0.422 \pm .021$ CPM/DPM. Complete calculation of the efficiency is in Appendix B. A Multichannel Analyzer made by Nuclear Data Incorporated was operated in the multichannel scaling mode to monitor and record the counts. The counts were recorded for 20 second intervals. This setup was useful in that it provided a visual indication of the counts detected and also allowed the collected data to be stored on 8 inch floppy computer discs.

Counting Method and Analysis. The calculation of the radon progeny with the gross alpha counting technique was based upon the Tsivoglou method described in Chapter II. The counting intervals chosen in this study were the 2-5 minute, 6-20 minute, and 21-30 minute intervals recommended by Thomas. The calculations for the daughter activity concentration were programmed in MBASIC for an Epson QX-10 computer. This program will calculate the concentrations for any sample and counting intervals. The program will also calculate the uncertainty in the

concentrations taking into account the error in air flow, detector efficiency and counting statistics. Additionally the program will calculate the value for the Working Level based upon the daughter concentrations. A listing of the program is provided in Appendix D.

Radon Progeny Removal Device. The air treatment device investigated in this thesis was an electrostatic precipitator or electronic air cleaner (EAC). The EAC used in this study is a commercial product developed by Honeywell Corporation. It is intended to be used as part of the central heating and air conditioning system in the home. The EAC consists of a wire mesh pre-filter, used to trap large particle and debris, and a series of electrically charged plates where the radon progeny are collected. The entire element can be removed from the system for easy cleaning. For the purpose of this thesis a special setup was built by a local contractor. The EAC was placed in a duct that was connected directly to a high volume air blower capable of drawing air through at a rate of 34000 l/min. The electronic air cleaner reduces the radon progeny concentration by creating an intense electric field between the parallel plates. As the blower draws the air through, the dust particles pass through the plates where they are collected and thus removed from the air.

V. <u>Results</u>

Radon Gas Concentrations

The environmental measurements for radon gas were made using the 3.77 liter Lucas cell. The locations and times of the measurements before and after start of gas generation are listed in Tables II and III respectively. The tables also list the values of radon gas concentration calculated for each sample.

TABLE II

Ambient Radon Gas Concentration
Levels Before Release of Radon Gas

Location	Date/Time	Radon Concentration (pCi/l)
Workshop	29 Oct/1618	0.022 ± 17%
Outside	30 Oct/0844	0.037 ± 22%
Control Room	30 Oct/1718	0.078 ± 17%
Workshop	30 Oct/1500	0.023 ± 9.1%

TABLE III

Radon Gas Concentrations
After Start of Radon Gas Flow

Location	Date/Time	Radon Concentration (pCi/l)
Workshop	7 Nov/1404	0.030 ± 12%
Outside	8 Nov/0951	0.022 ± 50%
Basement	8 Nov/1610	0.042 ± 12%
Control Room	11 Nov/1720	0.215 ± 5%

TABLE IV

Radon Gas Concentration in Test
Chamber Before Sealing Air Infiltration

Date/Time	Radon Concentration (pCi/L)
5 Nov/1410	0.611 ± 3.1%
6 Nov/0900	1.55 ± 4.0%
6 Nov/1431	0.886 ± 2.6%
7 Nov/0902	1.41 ± 4.0%
9 Nov/1614	0.647 ± 3.4%

As can be seen by quick inspection, the rela ve changes in the values in Tables II and III are on the order of 0.01 pCi/liter. With the exception of the value listed for the control room, all were within the uncertainty of the value; therefore, no significant increases were noted. The control room is adjacent to the radon test chamber and for a short time air was blowing from the test chamber into the control room. The source of the unwanted air was found to be air blowing into the chamber from the rear service entrance to the building. This source was sealed and the blowing into the control room was stopped. This additional air also caused large fluctuations in the radon test chamber gas concentrations making it impossible to achieve a steady state. Values for air samples taken of the test chamber are listed in Table IV. As is clearly seen from Table IV steady-state concentrations were not achievable because of the influx of uncontrolled air.

During the period 7 - 12 December air samples were again taken outside the shop area. The samples were taken using the 3.77 liter large Lucas cell. The calculated values for the radon gas concentration from the data collected are listed in Table V.

TABLE V

Radon Gas Concentration
From Outside Shop Area

Date/Time	Radon Concentration (pCi/1)
7 Dec/1420	0.283 ± 6.2%
10 Dec/0859	0.445 ± 14.9%
10 Dec/1427	0.115 ± 10.4%
11 Dec/0915	0.113 ± 13.0%
11 Dec/1558	0.0008 ± 15.0%
12 Dec/0856	0.143 ± 11.0%
12 Dec/1522	0.104 ± 13.0%

The noted increase in the gas concentration measured here, as com-
pared to values obtained in October, is a result of changes in atmospheric
conditions, primary changes were in outdoor temperature and winds. The
overall result of these measurements is that no high levels or potentially
dangerous level of radon gas was introduced into the surrounding environ-
ment either in or outdoors. The maximum permissible concentration of
radon in air is 3×10^{-6} microcurie/liter of air (6:490), which is 3
pCi/1. The highest value measured with our Lucas cell was 0.445 pCi/1,
well within the maximum permissible concentration in the air.

As was stated earlier, the measurement of the daughter concentrations
would be made when a steady-state concentration of the radon gas was
achieved in the chamber. To monitor the gas concentration in the chamber,
several air samples were collected with the RCTS. The results of the
sample run are contained in Table VI. The average steady state value of
the gas concentration during the course of this study was 9.98 ± 0.42%
pCi/liter.

TABLE VI

Radon Gas Concentrations
in Test Chamber Using the RCTS

Date	Radon Concentration (pCi/L)
*14 Nov	6.65 ± .15%
16 Nov	12.19 ± .18%
**21 Nov	9.39 ± .18%
**29 Nov	8.10 ± .20%
6 Dec	10.25 ± .21%
Average	9.98 ± .42%

* - Sample collected prior to sealing rear
     door in test chamber
** - Sample collected 8 hours after start of
      air treatment device

Radon Progeny Measurements w/ Electrostatic Precipitator

During the period 19 November - 9 December 1984, nine different runs
with the electrostatic precipitator were made to measure the effectiveness
of the precipitator in reducing the working level or potential alpha
energy, as a function of radon daughter concentration. The runs fell into
three categories: 1) two runs made with just the blower fan in operation,
2) four runs made with the precipitator and blower in operation, 3) three
runs were made with half of the air intake to the precipitator blocked
off in an effort to reduce the air flow. The air flow through the pre-
cipitator was measured to be approximately 34000 liter/minute of air.
This equates to roughly 20 complete air changes per hour.

Category 1. The two runs in this category were made on 19 and 21
November. In each of these runs only the blower fan was used to draw

air through the filters and precipitator. Initial measurements of the
daughter concentrations and working level were made before the start of
the blower. The fan was then turned on and allowed to run for 15 min-
utes before the daughter samples were started. The samples were then
collected approximately every thirty minutes thereafter. Figures 6 and
7 show graphically the reduction noted in the working level and daughter
concentration as a result of the fan blowing. The reductions are caused
by a trapping of the daughters in the pre-filter of the precipitator and
to increased plateout of the unattached daughters on the walls. The
measured reduction of both samples was averaged and found to be 75 percent.

Category 2. In this category four runs were made to measure the
effective reduction of the daughters and working level as a result of
electrostatic precipitator operation. The first run was made on 26 No-
vember. As with the measurements in category 1, samples were first col-
lected with no air treatment devices in operation. The EAC was started
and 15 minutes were allowed to pass before the first sample with the air
treatment device was taken. Subsequent samples at thirty minute intervals
were then taken. After sample 8 was collected the EAC and blower fan
were turned off. One hour later daughter samples were again taken to mea-
sure the ingrowth of the daughter products. The reduction and ingrowth
for this run is shown in Figure 8. The overall measured reduction in
working level was 90 percent. It is interesting to note that within one
and a half hours after the EAC was stopped the working level and daughter
concentrations were almost at the beginning point as measured before the
EAC was started. The average reduction for each daughter was 58, 95 and
96 percent for Ra-A, Ra-B and Ra-C respectively.

Figure 6. Run 1 Plot of Working Level and Daughter
Concentrations With Blower Fan Only

Figure 7. Run 2 Plot of Working Level and Daughter
Concentrations With Blower Fan Only

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Figure 8. Run 1 Plot of Working Level and Daughter
Concentrations With EAC in Operation

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Run 2, made on 2⁷ November, was identical to the samples collected in Run 1; the only difference of note is that only one sample was collected with no air treatment device in operation. The remainder of the procedures were exactly the same. As shown in Figure 9 an overall reduction of 90 percent in working level was experienced as a result of operating the EAC. The corresponding reductions in the daughter concentrations of 68, 95 and 96 percent for each of Ra-A, Ra-B and Ra-C were noted. Within thirty minutes of stopping the EAC the daughters and working level had again raised to a level near the concentration level at the start of this run.

Runs 3 and 4 were made with the same procedures as used in the two previous runs. The only exception is that run 4 samples were taken after the EAC had been operating for a period of 24 hours. This was done in an attempt to detect any noticeable degradation in the effectiveness of the precipitator due to saturation of filter or long operations. As can be seen in Figures 10 and 11 no significant changes were noted in the operation after the 24 hour period. The overall reduction in working level was found to be 90 percent, which is the same value found for the two previous runs. The reductions in daughters were 52, 92 and 97 percent.

Category 3. As can be seen in Figures 8 - 10, within the first 15 minutes of operation the EAC had reduced the working levels and daughter concentrations to the lowest level obtainable. In an attempt to try to fit the reduction curve within the first 15 minutes the air intake was reduced. This was done by sealing one half of the intake with paper. The first run in this category was made using the same sample and start

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WORKING LEVEL vs TIME EAC OPER

DAUGHTER CONCENTRATIONS vs TIME

Figure 9. Run 2 Plot of Working Level and Daughter
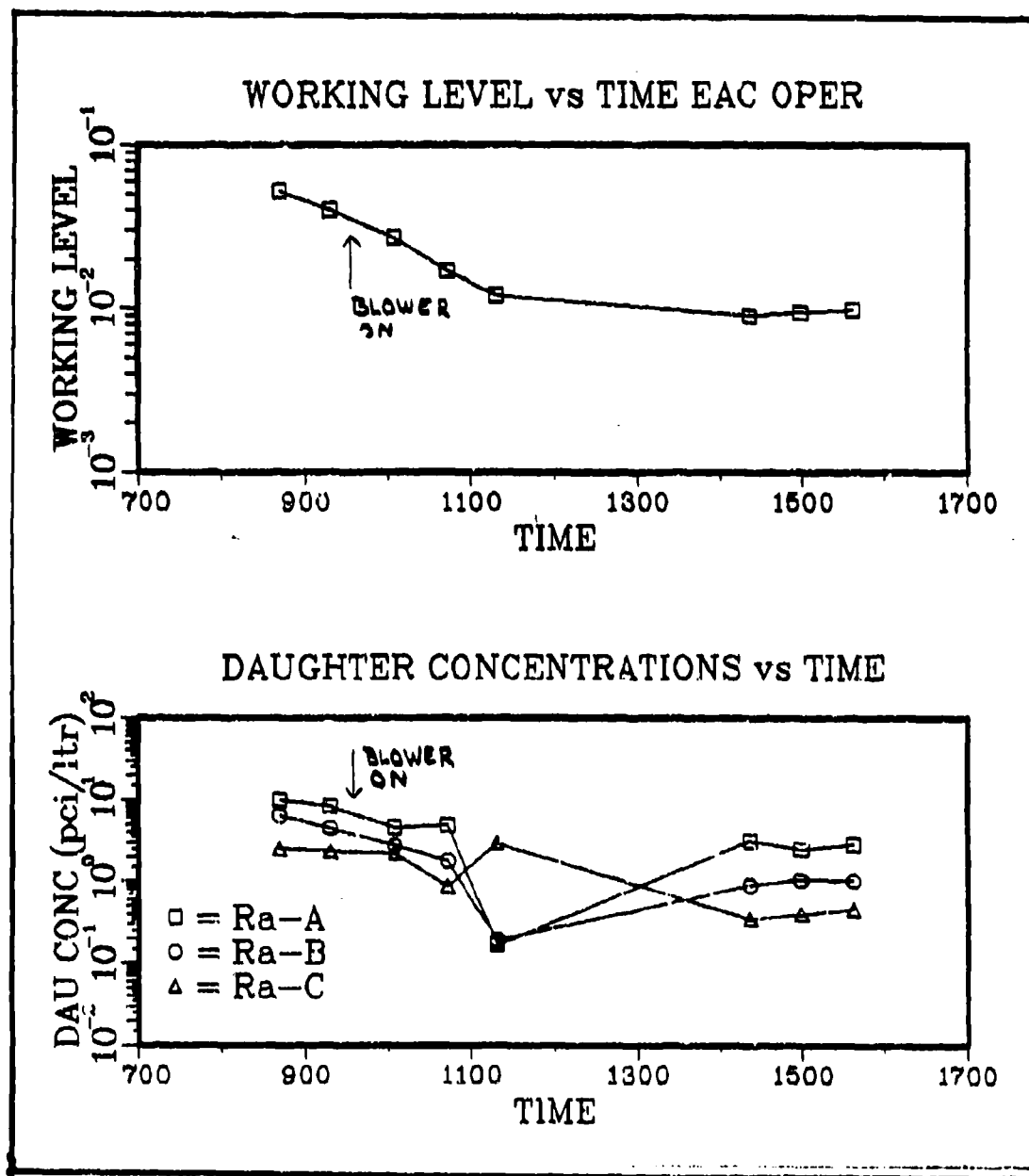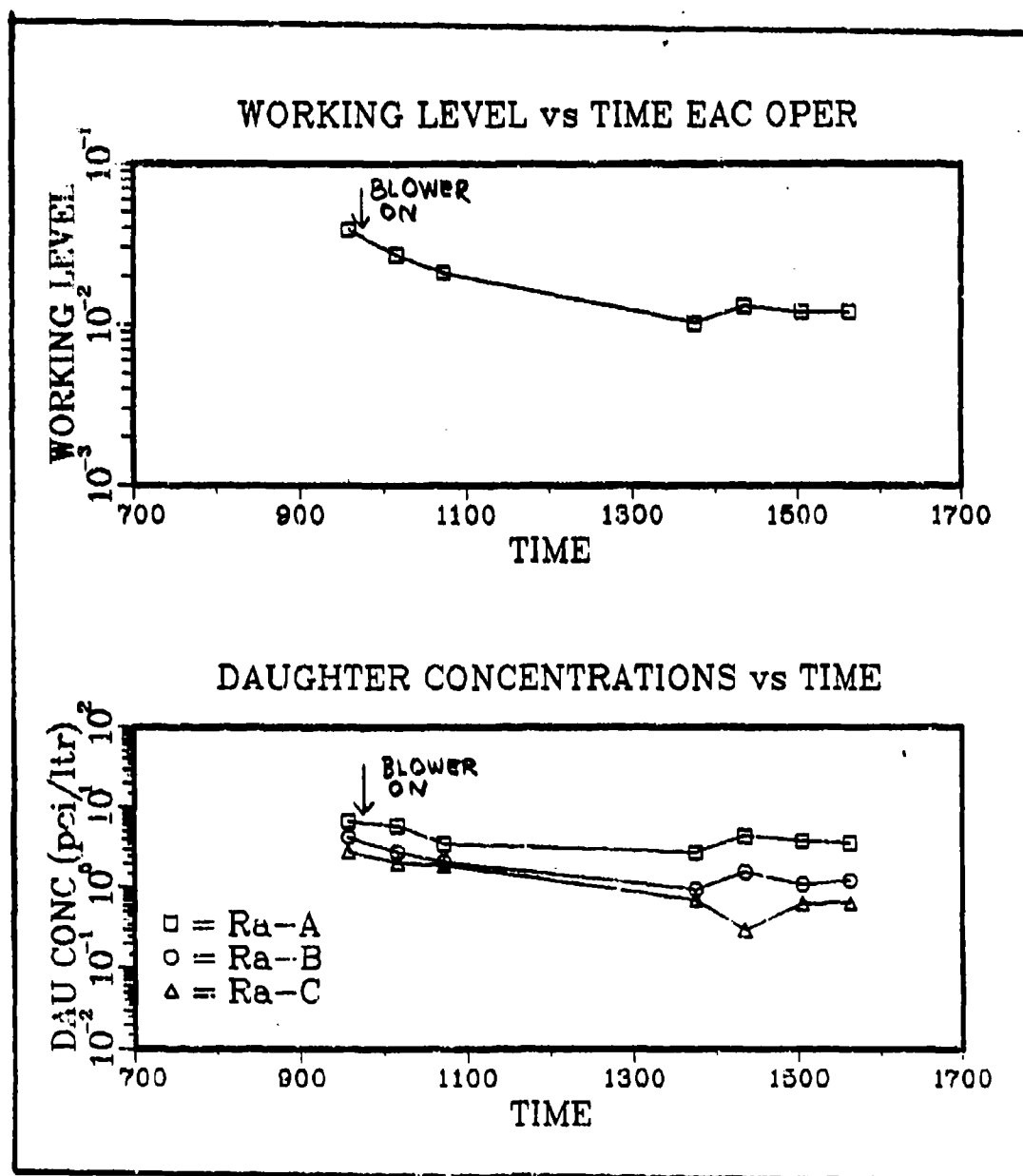Concentrations with EAC in Operation

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Figure 10. Run 3 Plot of Working Level and Daughter
Concentration With EAC in Operation
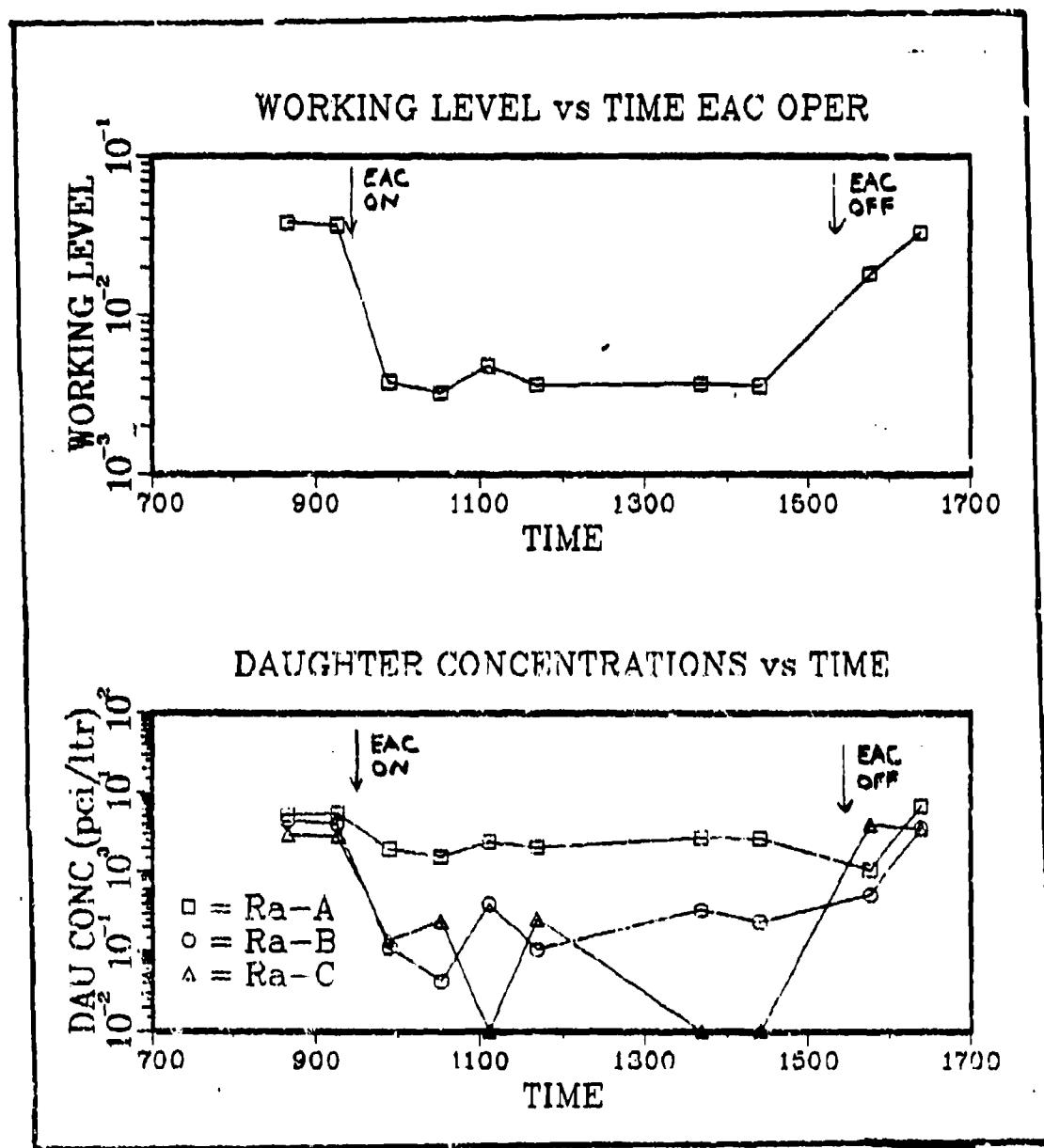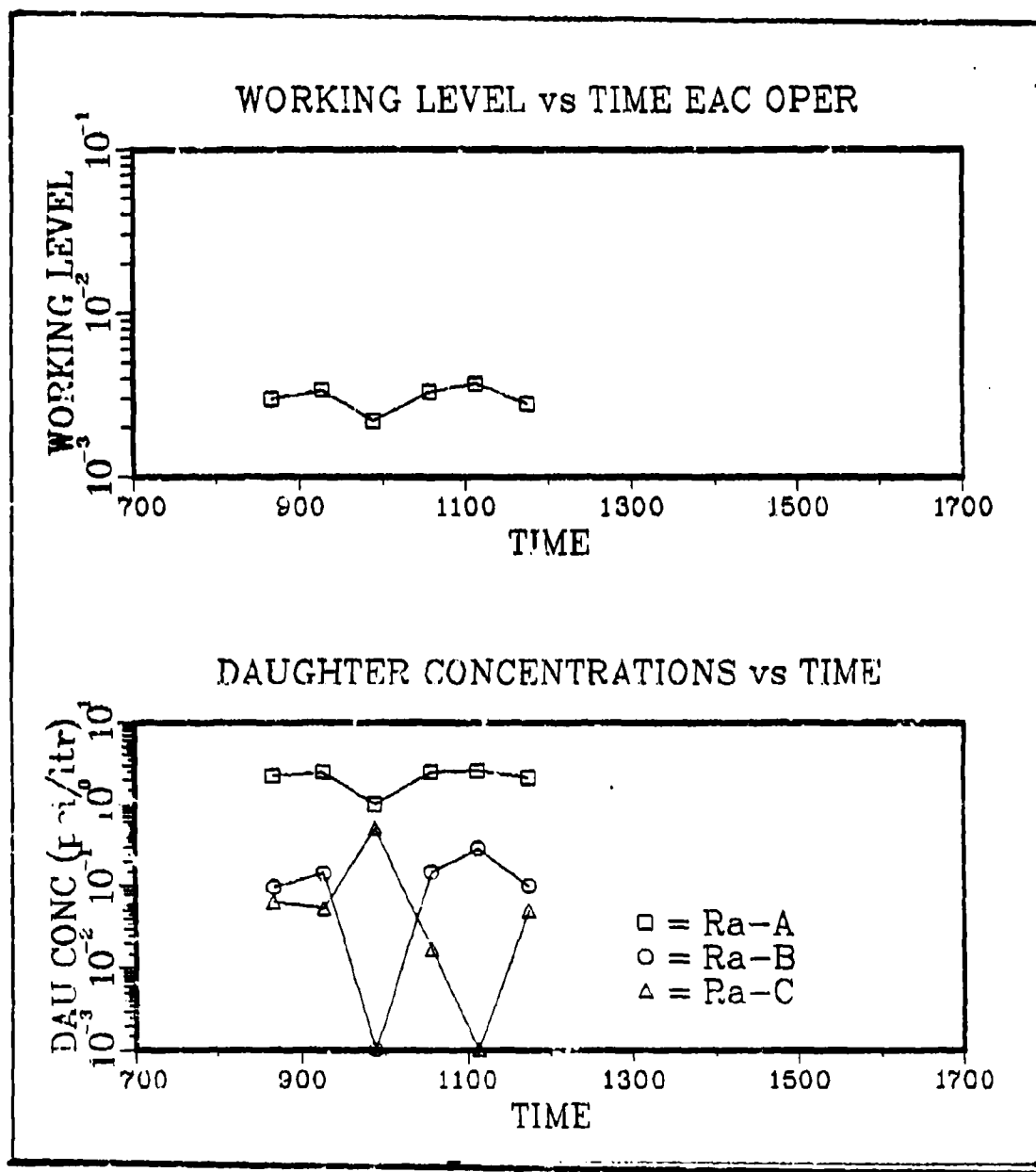
Figure 11. Run 4 Plot of Working Level and Daughter Concentrations After EAC on 24 Hours

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times as with the previous samples, i.e., 15 minutes after start of EAC the first sample was collected. Figure 12 shows the working level still reduced to the lowest obtainable level within the first 15 minutes. The overall reduction measured was 86 percent for the working level and 50, 77 and 97 percent for each of the daughters. For the next two runs the time delay between the start of EAC and collection of the first sample was shortened to 5 minutes with subsequent samples taken every thirty minutes thereafter. From Figures 13 and 14 a gradual reduction in the working level would tend to indicate the reduction is linear. The over-all reduction in working levels for these last runs were 93 and 90 percent respectively. The average reductions in the daughters for these runs were 84, 97 and 97 percent for run 2 and 67, 95 and 99 percent for run 3.

Daughter Concentrations. In each of the figures 6 - 14 a plot of the radon daughters concentration versus the Electronic Air Cleaner operation time is shown. The variations in the daughter concentration levels are a result of the high degree of disequilibrium between the radon gas and its daughters. The reduction in Ra-A, the upper line, shows an average reduction of 58 percent with the short half life of 3.05 minutes and 30 minute delay between sample collection. The concentration of Ra-A was nearly in equilibrium with the radon gas at all times. The second two drughters with half-lives of 26 and 19 minutes are never in equilibrium with their parent, as the 30 minute sample did not allow sufficient time for ingrowth of the daughters. As a result of this, the daughter concentration of Ra-B and Ra-C were constantly fluc-tuating as can be seen in each figure.

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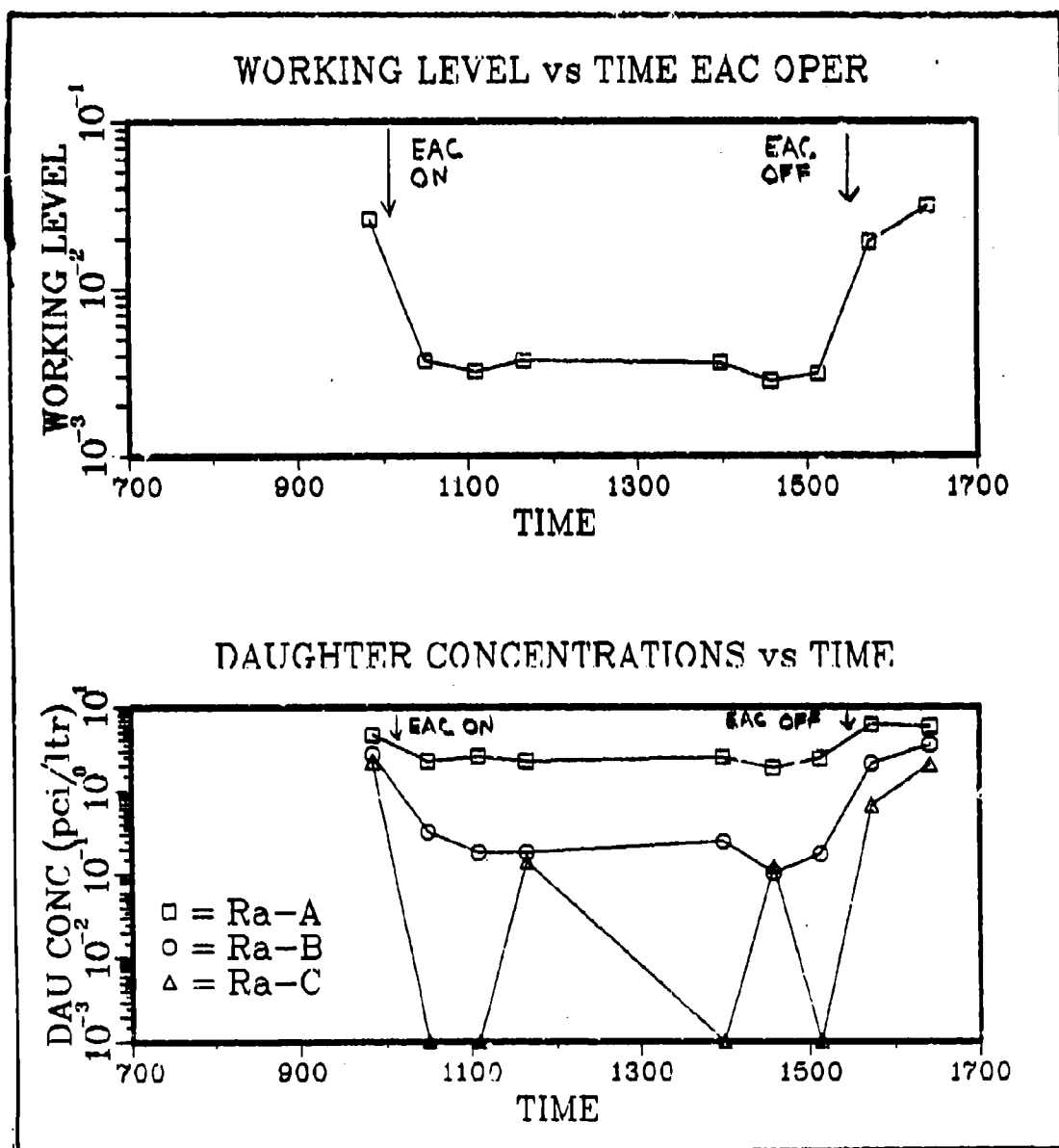
Figure 12. Run 1 Plot of Working Level and Daughter
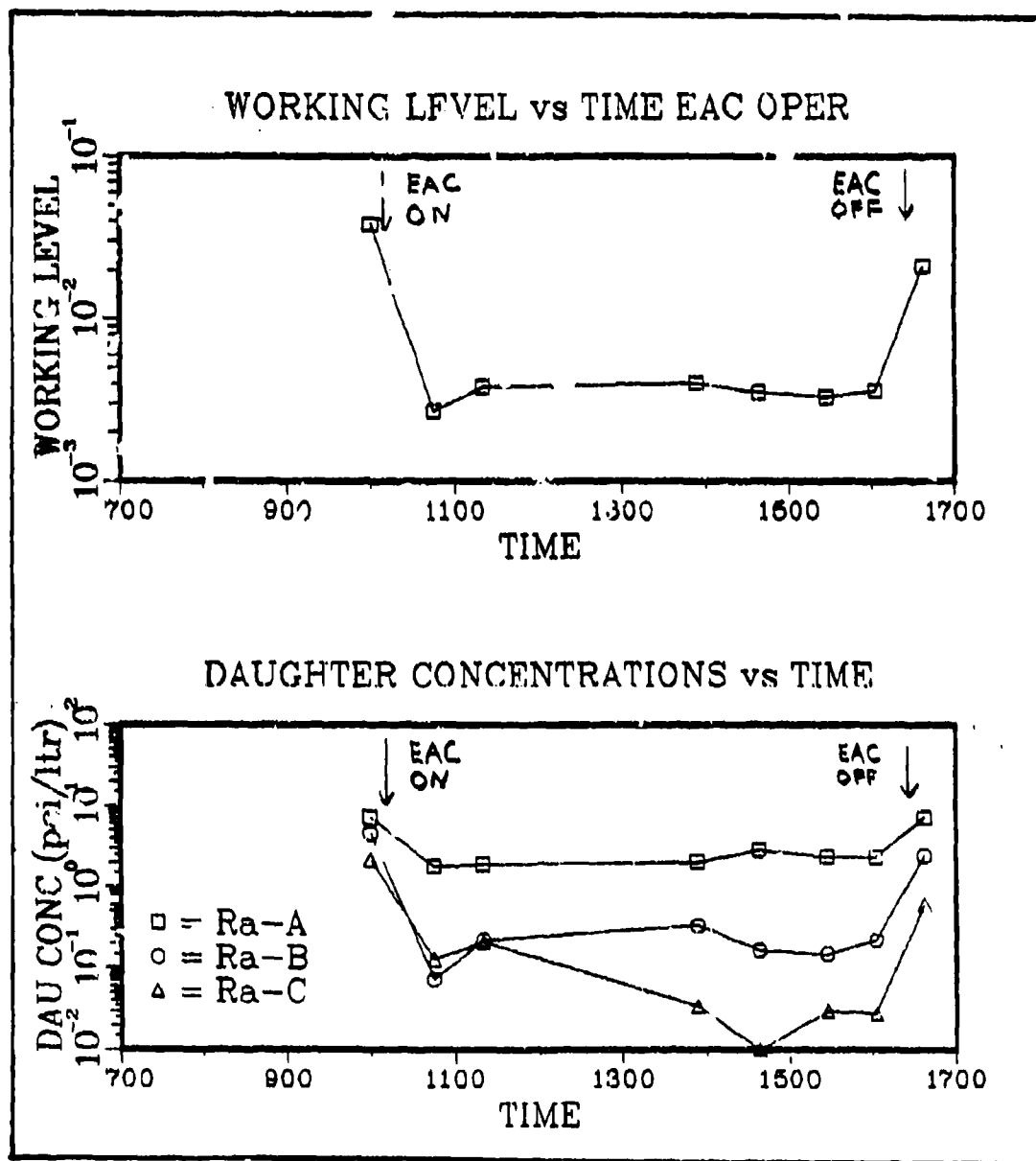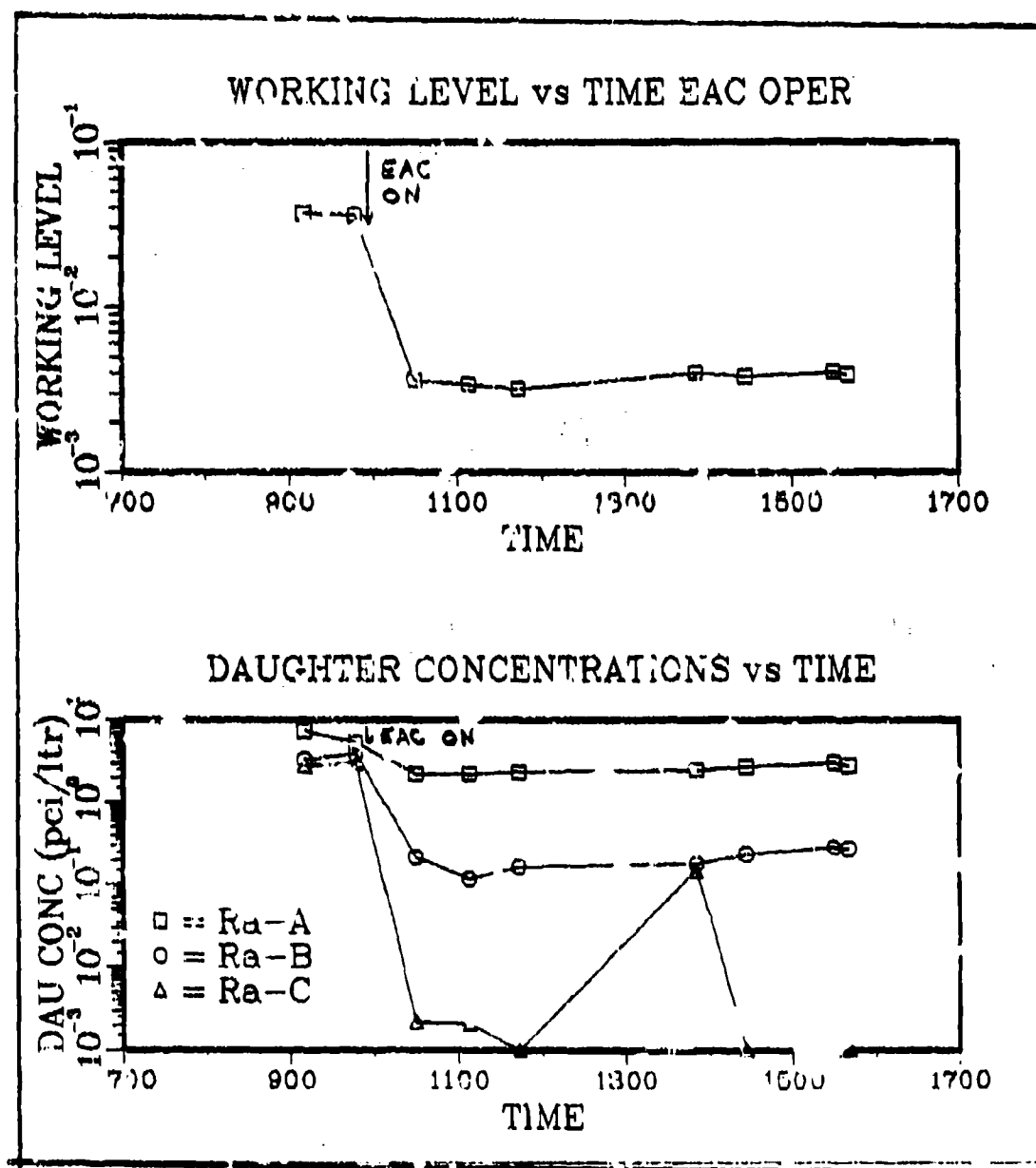Concentrations With Half Intake Sealed
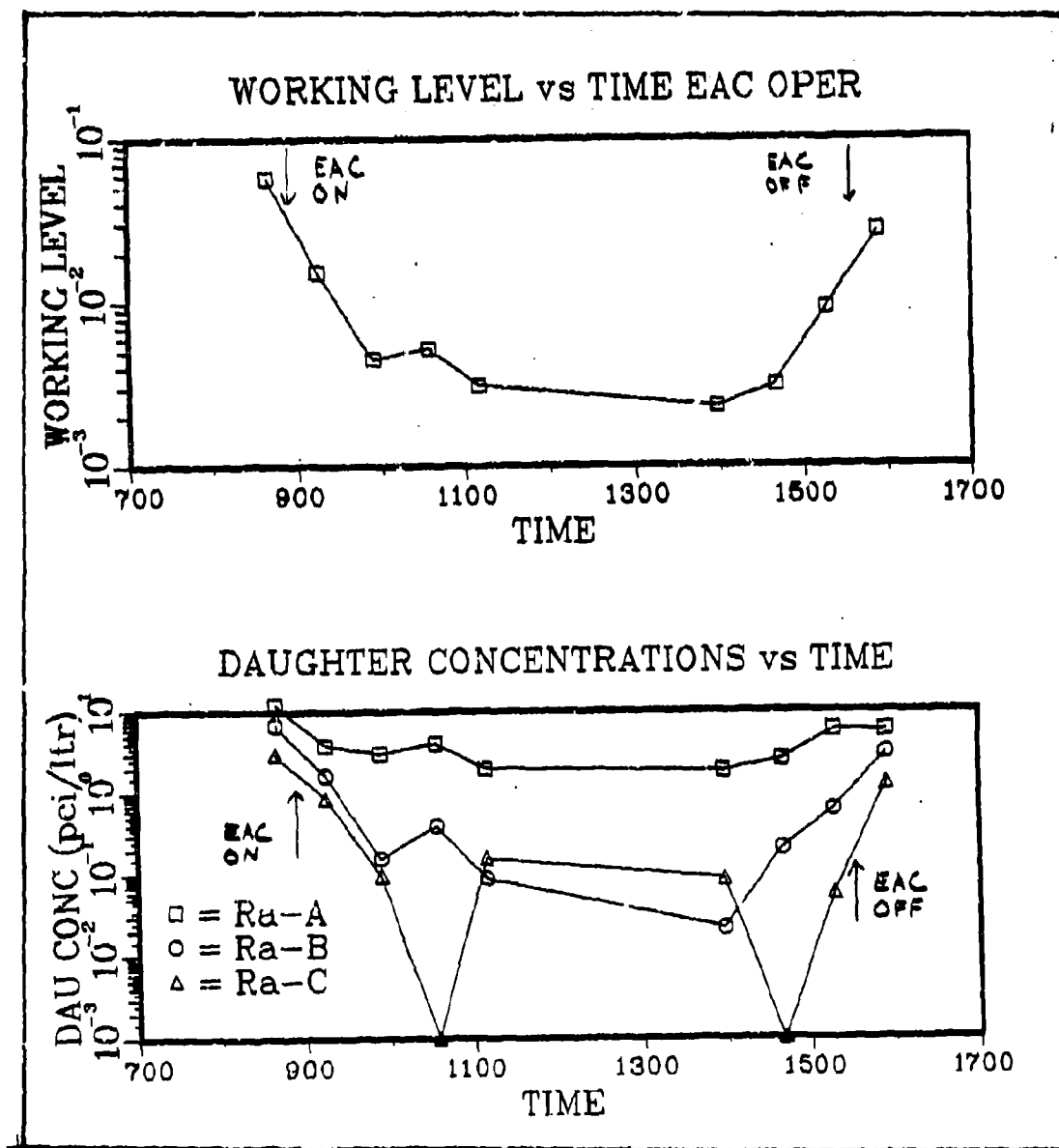
Figure 13. Run 2 Plot of Working Level and Daughter Concentrations With Half Intake Sealed
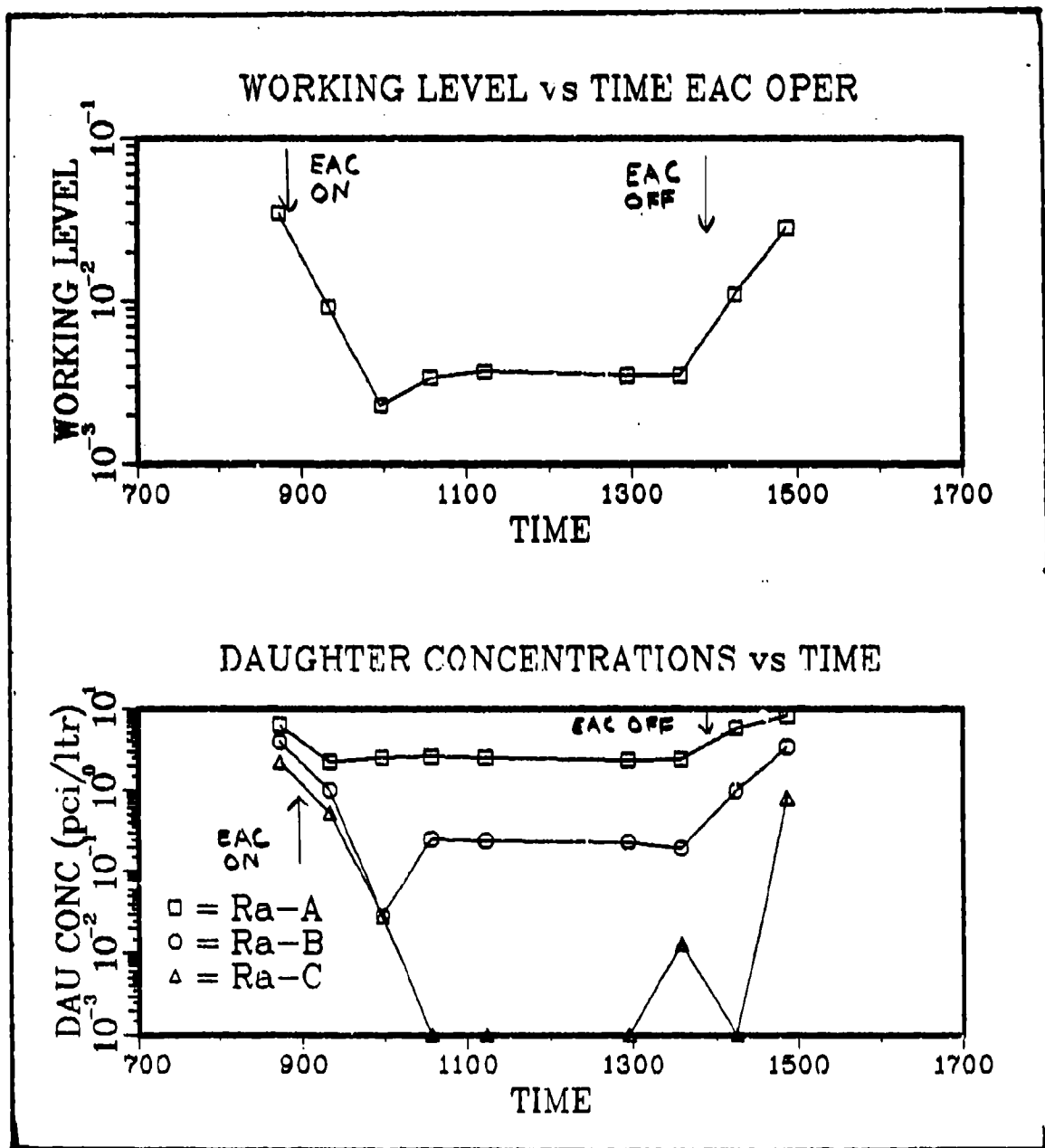
Figure 14.   Run 3 Plot of Working Level and Daughter
Concentration With Half Intake Sealed

VI. Conclusion and Recommendations

Conclusion

The objective of this thesis was to determine the effectiveness of using an electrostatic precipitator as a means for reducing the airborne concentrations of radon progeny in homes.

To achieve this goal several preliminary steps had to be accomplished. The first of these was to introduce radon gas into a test chamber and achieve a steady-state concentration of radon gas and its progeny. Due to uncontrolled air infiltration and removal of progeny by other methods beyond the scope of this project, a quasi-steady state was achieved. The average steady state gas concentration during the course of this project was 9.98 pCi per liter of air in the chamber.

The next step was to develop the theory and analysis to calculate the daughter concentration and associated working level. This was done using the modified Tsivoglou method. The errors in the calculated values were due to the uncertainty in the air flow and efficiency which were 4.5 and 4.9 percent respectively. Also errors were introduced by the counting statistics due to randomness of the decay process. A Poisson distribution was assumed for the counting statistics. As a result of extreme degrees of disequilibrium in daughter concentration the error associated with the counting statistics was notably high. The errors in the daughter concentration levels ranged from 12.6 to 431 percent for Ra-A, 5.3 to 235 percent for Ra-B and 9.8 to 531 percent for Ra-C. The largest error in the daughter concentrations was noted when the

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disequilibrium value was high after the precipitator had been on for several hours. The average error in the working level was 20 percent.

The final step in meeting the objective of this project was to take air samples with the electrostatic precipitator in operation to measure the reduction in the daughter concentrations and working level due to the precipitator. In all of the measurements that were made the precipitator reduced the working level by as much as 90 percent. This reduction usually occurred within 15 minutes after start of the precipitator.

From the data collected and analyzed results, the electrostatic precipitator is an effective method to use in reducing the radon daughter concentrations in homes.

Recommendations

In an effort to improve the results and better evaluate the effectiveness of using the electrostatic precipitator the following recommendations are suggested:

1. Submit work order to fabrication shop to have seals made for all heating and air conditioning ducts, and seal off all cracks and holes in the walls and doors. Then using a tracer gas make detail measurements of the air infiltration rates in the room.

2. To effectively study the impact of humidity and temperature on the concentrations of radon progeny, submit work order to install controls, which can be operated from outside the test chamber, which control appropriate equipment to regulate the humidity and temperature in the test chamber, i.e., dehumidifier and heaters. A humidifier is available with the present setup.

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3.   Determine the amount of daughters which are removed from the air due to increased air circulation within the test chamber while the blower fan is in operation. This will give a more accurate value of the reduction in daughter concentration caused by the precipitator.

4.   Using the present setup and procedures, continue work with the weighted least square regression method of analysis to determine the sensitivity or error in the method. Then compare the error results against the modified Tsivoglou method.

5.   Conduct studies of the modified Tsivoglou method under conditions of extreme disequilibrium to obtain optimised values for sample collection and counting times. Conditions of extreme disequilibrium will be achieved within an hour after starting the precipitator.

Appendix A: Elements of the K and L Matrices Used in
Calculating Radon Progeny Concentrations

This appendix lists the specific expressions for the elements of
the K and L matrices used in solving for the airborne concentrations of
each radon daughter product.

The elements of the K matrix used in calculating the number of
atoms present on the filter after sample collection are:

$$k_{11} = \frac{1}{\lambda_1}\left(1 - e^{-\lambda_1 t_s}\right) \tag{23}$$

$$k_{12} = k_{13} = k_{23} = 0 \tag{24}$$

$$k_{21} = \frac{1}{\lambda_2}\left(1 - e^{-\lambda_2 t_s}\right) + \frac{1}{\lambda_1 - \lambda_2}\left(e^{-\lambda_1 t_s} - e^{-\lambda_2 t_s}\right) \tag{25}$$

$$k_{22} = \frac{1}{\lambda_2}\left(1 - e^{-\lambda_2 t_s}\right) \tag{26}$$

$$k_{31} = \frac{1}{\lambda_3}\left(1 - e^{-\lambda_3 t_s}\right) + \frac{\lambda_2}{(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_1)}\left(e^{-\lambda_1 t_s} - e^{-\lambda_3 t_s}\right)$$

$$+ \frac{1}{\lambda_3 - \lambda_2}\left(e^{-\lambda_3 t_s} - e^{-\lambda_2 t_s}\right) + \frac{\lambda_2}{(\lambda_3 - \lambda_2)(\lambda_1 - \lambda_2)}\left(e^{-\lambda_2 t_s} - e^{-\lambda_3 t_s}\right) \tag{27}$$

$$k_{32} = \frac{1}{\lambda_3}\left(1 - e^{-\lambda_3 t_s}\right) + \frac{1}{\lambda_3 - \lambda_2}\left(e^{-\lambda_3 t_s} - e^{-\lambda_2 t_s}\right) \tag{28}$$

$$k_{33} = \frac{1}{\lambda_3}\left(1 - e^{-\lambda_3 t_s}\right) \tag{29}$$

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The elements of the L matrix used to calculate the number of alpha disintegrations in a time interval $t_{n1} - t_{n2}$. Where t_{n1} and t_{n2} are the start and stop count times for each post sample count interval. The L elements are:

$$l_{n1} = \left[e^{-\lambda_1 t_{n1}} - e^{-\lambda_1 t_{n2}} \right] + \left[\frac{\lambda_2 \lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)} \right] \left[e^{-\lambda_1 t_{n1}} - e^{-\lambda_1 t_{n2}} \right]$$

$$+ \frac{\lambda_1 \lambda_2}{(\lambda_3 - \lambda_2)(\lambda_3 - \lambda_1)} \left[e^{-\lambda_3 t_{n1}} - e^{-\lambda_3 t_{n2}} \right]$$

$$+ \frac{\lambda_1 \lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_2)} \left[e^{-\lambda_2 t_{n2}} - e^{-\lambda_2 t_{n1}} \right] \tag{30}$$

$$l_{n2} = \frac{\lambda_3}{(\lambda_3 - \lambda_2)} \left[e^{-\lambda_2 t_{n1}} - e^{-\lambda_2 t_{n2}} \right] + \frac{\lambda_2}{(\lambda_3 - \lambda_2)} \left[e^{-\lambda_3 t_{n2}} - e^{-\lambda_3 t_{n1}} \right]$$

$$\tag{31}$$

$$l_{n3} = \left[e^{-\lambda_3 t_{n1}} - e^{-\lambda_3 t_{n2}} \right] \tag{32}$$

Appendix B: Calculation of Efficiencies for the Large
Lucas Cell and the Alpha Counting System

The calculation of the large lucas efficiencies was made using a known concentration of radon gas obtained from Monsanto Mound Laboratories. The gas concentration was 51.74 pCi/liter (8). The sample was allowed to obtain equilibrium before counting started. The Lucas cells had a volume of 3.77 liters, giving a total activity of 195 pCi. At equilibrium, for every decay of radon gas, three alpha particles are emitted.

Lucas cell 1 had a delay of 20175 seconds from time of collection to start of counting; the activity in the cell was then 187 pCi. This gives a value of 5.61 disintegrations per second. Lucas cell 2 had a delay of 73740 seconds, giving an activity of 167 pCi, for 5.01 disinte-grations per second. From these values the expected counts for a given time interval can be determined. Table VII lists the expected and observed counts for a 20000 second count interval and the efficiencies of each Lucas cell.

The efficiency of the gross alpha counting system for counting the filter papers was determined using a 22mm disc source of RaD+E which had an activity of 508 dps on 1 January 1953. This value is on file with the Physics Laboratory and was provided by the National Bureau of Standards. The expected count is determined from the equation

$A = A_0 *$ EXP $(-\lambda t)$. Taking λ to be $8.5 \times 10^{-5} d^{-1}$ and $t = 11634$ days, the expected activity is 188 disintegrations per second. For a count

TABLE VII

Efficiency of the Large Lucas Cells and
Alpha Counting Systems With Error

System	Expected	Observed	Efficiency ± Error
Lucas Cell #1	336600	75096	0.22 ± .5%
Lucas Cell #2	300600	83550	0.28 ± .4%
Alpha Counting	735880	319337	0.422 ± 4.9%

interval of 4000 seconds the expected counts are 755880. The observed
counts for the source in 4000 seconds was 319337, resulting in an abso-
lute efficiency of 0.422.

The error in the efficiencies can be determined by application of
the standard error propagation formula. Given a 5 percent error in the
source activities and assuming Poisson distributed counting statistics,
the errors can be calculated quite easily.

Appendix C: Procedures for Use of the Radon Collection
and Transfer System (RCTS)

This appendix will explain the step by step procedure to be followed
for processing an air sample through the RCTS. A diagram of the RCTS is
shown in Figure 15.

The purpose of the RCTS is to take a sample of air assumed to con-
tain radon gas, process the sample through a series of traps to remove
the water vapor and carbon dioxide and then trap the radon gas in a char-
coal filter. Once separation of these elements has been accomplished,
the radon gas is then transferred into a Lucas Cell, where the radon gas
and its progeny decay by alpha emission. The disintegrations are then
detected by a photomultiplier tube and counted. The initial concentra-
tion of the gas can then be calculated using an integrated count method
developed by Jonassen (17:350).

To insure the radon gas collected in the Lucas Cell is not contam-
inated with gas from the ambient air in the RCTS, it is evacuated. This
is done by opening valves 2, 3, 8 and allowing the vacuum pump to draw
all the air from the system through valve 8. The pump should be allowed
to run until the vacuum thermocouple gauge reads about 30-40 microns.
When evacuation is completed, close valves 2 and 3.

To evacuate the air sample collection tank, connect the tank to the
RCTS at valve 1. Open valve 1 and the air inlet valve on the air tank,
this will allow the air to be drawn through valve 8. When the tank is
evacuated then close all valves. The next step that should be performed
is to evacuate the Lucas Cell to be used in sampling the radon gas. This
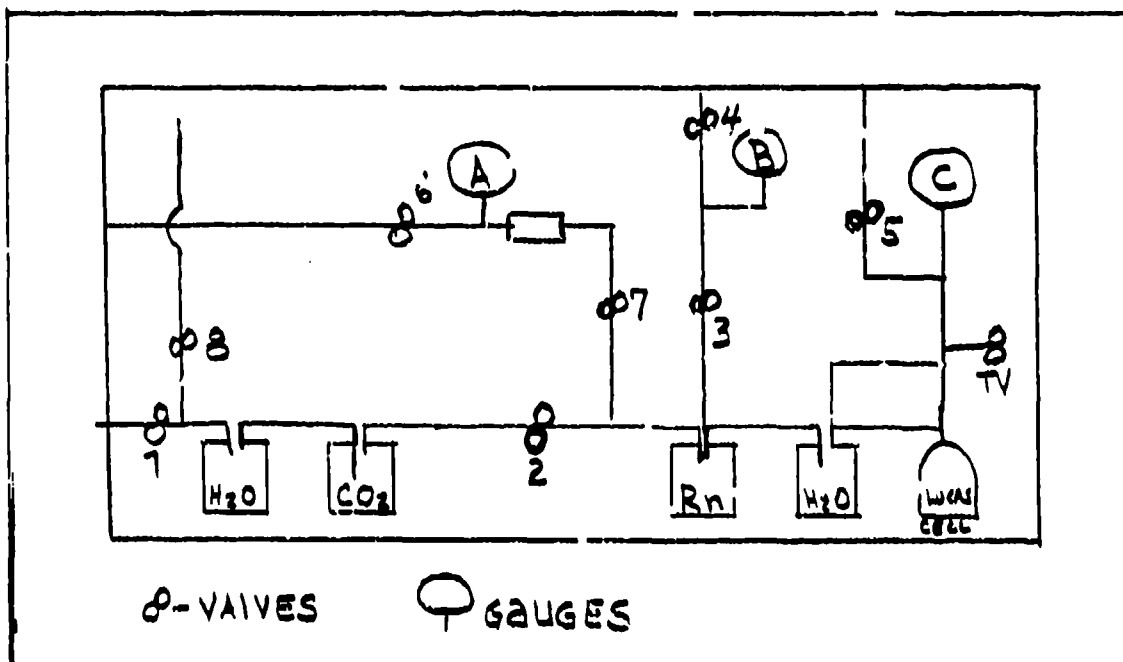
Figure 15. Diagram of the Radon Collection and Transfer System

is done by opening the stopcock on the cell and opening valve 5 on the
RCTS. This facilitates the evacuation through valve 5.

After the system. collection, and sample vessels have been evacuated,
cold baths are prepared for the water and radon traps. The baths are
prepared by mixing methyl, ethyl, or isopropyl alcohol and dry ice in
dewars. The traps should be brought down to a temperature of approxi-
mately -78° C. The purpose of these baths is to freeze the water vapor
in the sample in the water vapor trap and to freeze the radon gas in the
gas trap. The baths are slid over the two traps on the RCTS appropri-
ately marked. The time required to bring traps to the needed temperature
is approximately one hour.

The tank is then taken to the location where the air is to be drawn, the inlet valve is opened and the tank is allowed to fill with the sample. The tank will then be taken to the RCTS and connected at valve 1. At this time insure all valves on the RCTS are closed. Leaving the inlet valve on the tank closed, open valve 1 and 6 of the RCTS. This will evacuate the air which collected in the feed line, and could contaminate the sample with radon gas in an unknown volume. When evacuation is completed, usually in 45-60 seconds, close all valves.

The next phase of the process will be to draw the air sample from the tank and pull it through the water vapor, carbon dioxide, and radon traps. Accomplishment of this phase is done in the following steps. Open valves 1, 2, and 3 on RCTS and the inlet valve on the tank. This will pull the air from the tank up through the radon trap. At this time gauge B will zero out. The purpose now is to pull the air through the traps to separate the radon gas from the other elements. This is done by regulating the air flow with valve 4 which is connected to the vacuum pump. It is imperative that the flow through the system is not so fast that the radon gas does not have time to freeze and be caught in the radon trap. It is recommended that a minimum time of 15 minutes for 34 liters of air be used as a benchmark. Again, this flow is regulated by valve 4. When the sample has been drawn through the traps, the valves are then closed in the following sequence: tank inlet valve, valve 1, valve 2, valve 3, and finally valve 4. Record the time that this phase is complete as it is critical to the calculation of the gas concentration. The cold bath is now removed from the radon charcoal trap, an oven is

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raised over the trap and voltage applied to the heating element. The temperature is raised to approximately 400° C which takes approximately 60 minutes. When the trap has reached the desired temperature, then the next phase of transferring the gas to the Lucas cell will begin. This is done by first opening the valve on the helium tank. Open valve 6 on the RCTS until gauge A reads approximately 4 on the pressure dial. Close valve 6, open valve 7 which allows the helium gas to flow into the radon trap. The helium gas should be held in the radon trap for 5 minutes before transferring it to the Lucas cell. A small transfer pump, which pumps the gas from the trap into the Lucas cell is started at this time by plugging its power cable into an electrical outlet. The flow of the gas to the Lucas cell is regulated through the TV valve identified on sketch in Figure 15. While leaving valve 7 open and the pump running, slowly open the TV valve until the needle on gauge C begins to move, leave the valve open until the needle movement stabilizes. At stabilization close the TV valve and valve 7. Open valve 6 to allow more helium gas into the system, repeat the process until gauge C reads 0, indicating one atmosphere pressure in the Lucas cell. When transfer has been completed the Lucas cell, TV valve, valve 7 and helium tank are all closed. At this time the Lucas cell is removed from the RCTS and placed in a photomultiplier tube and counting of the sample can be started. The counts can be taken for any length of time desired. The gas concentration is then calculated using an integrated count method described by Jonassen (17:350). The efficiency of the RCTS has been determined by previous experimenters and is taken as 84 percent (8;11;37).

The value of 84 percent for efficiency of the RCTS was arrived at by processing a known concentration of radon gas through the system. The radon gas was collected by flowing air through a known concentration of radium in solution. Then processing the gas through the RCTS using the procedure outlined in this appendix, a value for radon gas concentration was calculated. This calculated value was then compared to the theoretical value, as determined from known radon gas emanation rate and radium solution concentration. The value of the efficiency includes contribution of the transfer, collecting and counting efficiency of the system; therefore, it is the total efficiency of the system.

In processing a sample of air with an unknown radon gas concentration, the value of efficiency for the system may be higher than 84 percent, this difference resulting from the fact that the process does not include the efficiency of radon gas emanation from the radium solution.

It is recommended that the efficiency of the system be verified. This can be accomplished by taking an air sample of known radon gas concentration and processing it through the RCTS. The sample may be provided by the Monsanto Mound Laboratory in Centerville, Ohio.

Appendix D: Computer Programs Used in Math Analysis

This appendix lists the computer programs used in performing the calculations for this thesis. The first listing is the program used in calculating the radon gas concentrations using an intergated count method (16). The second listing is the program for the modified Tsivoglou method used in determining the daughter concentrations. Both programs were written in MBASIC for use on an Epson QX-10 computer system. The third listing is a weighted least square regression method used in determining the daughter concentrations. It is written in Fortran 5 for use on a Zenith Z-100 computer system with Z DOS operating system.

```
20 REM THE PROGRAM USES THE INTEGRATED COUNT METHOD FOR THE RADON CON
CENTRATION.
30 REM FOR RADON DETERMINATIONS, THE PROGRAM REQUIRES. 1) RADON FREE
LUCAS CELL BACKGROUNDCOUNT AND COUNT INTERVAL LENGTH (IN MIN)0!
40 REM 2) TIME (MIN) BETWEEN SAMPLE COLLECTION AND COUNTING. 3) COUNTING
INTERVAL (MIN), AND 4) TOTAL COUNTS IN INTERVAL
50 PRINT "---LUCAS CELL DATA INPUT---"
60 INPUT "Lucas background interval (in Min) =";T2
70 INPUT "Lucas background count =";B2
80 INPUT "Lucas Cell Efficiency =";E2
90 INPUT "Time from sample to count (MIN) =";T3
100 INPUT "Counting interval length (min) =";T4
110 INPUT "Total counts =";G4
120 F=23904.80635#*(EXP(-.0001259*T3)-EXP(-.0001259*(T3+T4)))-4.50748*(EX
P(-.2272*T3)-EXF(-.2272*(T3+T4)))-165.51951#*(EXP(-.02586*T3)-EXP(-.02586
*(T3+T4)))
130 G=F+93.656*(EXP(-.03518*T3(-EXP(-.03518*(T3+T4)))
140 R=(G4-B2*T4/T2)/(E2*G*2.22)
150 D=100*(1/(2.22*E2*R*T4))^.5
160 R1=R/34.41
170 LPRINT CHR$(15);
180 PRINT "    "
190 PRINT "---LUCAS CELL DATA---"
200 PRINT "T1 = ";T3;"  Minutes"
210 PRINT "T2-T1 = ";T4;" Minutes"
220 PRINT "Counter Efficiency = ";E2;" CPM/DPM"
230 PRINT "Total Counts = ";G4
240 PRINT "Background count rate = ";B2/T2;"+/-";SQR(B2)/T2;"CPM"
250 PRINT "    "
260 LPRINT "    "
270 PRINT "---Radon Conc and Coeff of Variation---"
280 PRINT "Radon = ";R1;"PCI/L +/- ";D;" %"
290 LPRINT"  "
300 END
```

```
10 REM Program to calculate the radon progeny concentration using the
20 REM Thomas method (Modified Tsivoglou Method)
30 DIM A$(3),B$(3),A(3),C(3),D(3),E(3),F(3),G(3),Z(3)
40 DIM K(3,3),L(3,3),M(3,3),S(3,3),R(3,3),W(3),Y(3)
50 DIM B(2),T(6),U(3),V(3),P(3),J(3)
60 INPUT "Sample collection time";T
70 INPUT "Air flow rate (LPM) and uncertainty in %";V,X
80 INPUT "The effective efficiency of the system(detector and filter)
and uncertainty in %";G,Y
90 PRINT "The counts detected for each time interval"
100 INPUT "Counts in T1";G(1):PRINT
110 INPUT "Counts in T2 ";G(2):PRINT
120 INPUT "Counts in T3 ";G(3):PRINT
130 INPUT "Background count rate (CPM) ";B
140 PRINT "Enter the start time(t1) and end time(t2) of each count interv
al"
150 INPUT "T1 and T2 for first interval";T(1),T(2)
160 INPUT "T1 and T2 for second count interval ";T(3),T(4)
170 INPUT "T1 and T2 for third count interval ";T(5),T(6)
180 A$(1) = "Ra-A" :B$(1) ="first"
190 A$(2)= "Ra-B":B$(2) ="Second"
200 A$(3) = "Ra-C" :B$(3) ="third"
210 D(1)= .2272 : D(2)= .02586 : D(3)= .03518
220 F(1) = D(2)-D(1)
230 F(2)= D(3)-D(1)
240 F(3) = D(3)-D(2)
250 FOR I = 1 TO 3
260 C(I) = (G(I) -B*(T(2*I)-T(2*I-1)))
270 Z(I) =SQR(G(I) + B*(T(2*I)-T(2*I-1)))/C(I)
280 NEXT I
290 K(1,1) = (1-EXP(-D(1)*T))/D(1)
300 K(1,2) = 0
310 K(1,3) = 0
320 K(2,1) = 1/D(2)-EXP(-D(1)*T)/(D(2)-D(1))+D(1)*EXP(-D(2)*T)/(D(2)*(D(2
)-D(1)))
330 K(2,2) = (1-EXP(-D(2)*T))/D(2)
340 K(2,3) = 0
350 K(3,1) = (1-EXP(-D(3)*T))/D(3)-D(2)*(EXP(-D(1)*T)-EXP(-D(3)*T))/(F(1)
*F(2))+D(1)*(EXP(-D(2)*T)-EXP(-D(3)*T))/(F(1)*F(3))
360 K(3,2) = (1-EXP(-D(3)*T))/D(3)+(EXP)-D(3)*T)-EXP(-D(2)*T))/F(3)
370 K(3,3) = (1-EXP(-D(3)*T))/D(3)
380 REM
390 REM Calculate the inverse of matrix K
400 GOSUB 1060
410 FOR I = 1 TO 3
420 L(I,1) = (1+D(2)*D(3)/(F(1)-F(2)))*(EXP(-D(1)*T(2*I-1))-EXP(-D(1)*T(2
*I)))+D(1)*D(3)/(F(1)*F(3))*(EXP(-D(2)*T(2*I))-EXP(-D(2)*T(2*I-1)))+D(1)*
D(2)/(F(2)*F(3))*(EXP(-D(3)*T(2*I-1))-EXP(-D(3)*T(2*I)))
430 L(I,2) =D(3)/F(3)*(EXP(-D(2)*T(2*I-1))-EXP(-D(2)*T(2*I)))+D(2)/F(3)*(
EXP(-D(3)*T(2*I))-EXP(-D(3)*T(2*I-1)))
440 L(I,3) = (EXP(-D(3)*T(2*I-1))-EXP(-D(3)*T(2*I)))
```

```
450 NEXT I
460 REM Calculate the inverse of matrix L
470 GOSUB 1310
480 REM
490 REM Multiply matrix s with matrix r
500 REM
510 FOR I = 1 TO 3
520    FOR J = 1 TO 3
530    M(I,J) = 0
520     FOR K = 1 TO 3
550    M(I,J) = M(I,J) + S(I,K)* R(K,J)
560    NEXT K
570   NEXT J
580 NEXT I
590 REM
600 REM return matrix m = s*r
610 REM
620 REM multiply matrix m with c
630 REM
640 FOR I = 1 TO 3
650   Y(I) = 0
660     FOR K = 1 TO 3
670     Y(I) = Y(I) + M(I,K) * C(K)
680     NEXT K
690 NEXT I
700 REM
710 REM
720 REM multiply matrix y with 1/gv
730 REM
740 FOR I = 1 TO 3
750   W(I)= (1/(G*V))*Y(I)
760 NEXT I
770 REM
780 FOR I = 1 TO 3
790 J(I) = ((Z(I)*C(I))/(G*V))^2
800 NEXT I
810 FOR I = 1 TO 3
820 U(I) = SQR(M(I,1)^2(*J(1)+(M(I,2)^2*J(2)+(M(I,3)^2)*J(3))
830 V(I) =(U(I)*100)/W(I)
840 P(I) = SQR(V(I)^2+Y^2+X^2))
850 A(I) = (D(I)*W(I))/2.22
860 NEXT I
870 E(1)= 1l
880 E(2) = (D(2)*W(2))/(D(1)*W(1))
890 E(3) = (D(3)*W(3))/(D(1)*W(1))
900 REM
920 REM print solutions
920 REM
930 FOR 1 = 1 TO 3
940 PRINT "***************** RADON PROGENY CONCENTRATIONS ***************
**"
950 PRINT "Counts for ";B$(I);" interval are "; G(I)
```

```
960 PRINT "Concentration is ";A$(I); " is ";A(I);"pCi/liter +/- ";P(I)
970 PRINT "Equilibrium concentration between Ra-A and ";A$(I);" is"E(I)
980 PRINT "************************************************************
*********"
990 PRINT:PRINT
1000 NEXT I
1010 PRINT "********************** WORKING LEVELS *********************
****"
1020 WI = .0010256*A(1)+.0050624*A(2)+.0037247*A(3)
1030 SI = SQR((.0010256)^2*(P(1)*A(1)/100)^2+(.005624)^2*(P(2)*A(2)/100)^
2+(.0037247)^2*(P(3)*A(3)/100)^2)
1040 PRINT "Working level = ";WI;" +/- "; (SI/WI)*100;"%"
1050 END
1060 FOR I = 1 TO 3
1070    FOR J = 1 TO 3
1080       S(I,J) = K(I,J)
1090    NEXT J
1100 NEXT I
1110 FOR I = 1 TO 3
1120  N = S(I,I)
1130    FOR J = 1 TO 3
1140      IF J = I THEN 1170
1150      S(I,J) = S(I,J)/N
1160      GOTO 1180
1170      S(I,J) = 1/N
1180    NEXT J
1190    FOR J = 1 TO 3
1200      IF J = I THEN 1280
1210      Q = -S(J,I)
1220        FOR K = 1 TO 3
1230          IF K = I THEN 1260
1240          S(J,K) =S(I,K)*Q + S(J,K)
1250          GOTO 1270
1260          S(J,K) = S(I,K) * Q
1270        NEXT K
1280    NEXT J
1290 NEXT I
1300 RETURN
1310 FOR I = 1 TO 3
1320    FOR J = 1 TO 3
1330       R(I,J) = L(I,J)
1340    NEXT J
1350 NEXT I
1360 FOR I = 1 TO 3
1370    N = R(I,I)
1380    FOR J = 1 TO 3
1390      IF J = I THEN 1420
1400      R(I,J) = R(I,J)/N
```

```
1410       GOTO 1430
1420       R(I,J) = 1/N
1430     NEXT J
1440     FOR J = 1 TO 3
1450     IF J = I THEN 1530
1460     Q = -R(J,I)
1470     FOR K = 1 TO 3
1480       IF K = I THEN 1510
1490       R(J,K) = R(I,K) * Q + R(J,K)
1500       GOTO 1520
1510       R(J,K) = R(I,K) * Q
1520     NEXT K
1530   NEXT J
1540 NEXT I
1550 RETURN
```

```
      PROGRAM RADON MAIN
C     SOLVES FOR THE INITIAL DISTRIBUTION OF A RADIOACTIVE CHAIN.
C     GIVEN SEQUENTIAL VALUES OF COUNTS EACH FOR THE SAME TIME
C     INTERVAL.
      DIMENSION A(10) ,Y(10) ,B(10) ,W(10) ,U(10,10) ,ZZ(10,10), Z(10)
      DIMENSION Q(10) ,CC(10,10) ,DA(10) ,LC(10) ,UU(10) ,TQ(10)
      DIMENSION YY(96),AL(10),P(10)
      CHARACTER*64 FNAME
      WRITE(*,'(A\)')'  INPUT FILE NAME?
      READ(*,'(A)')FNAME
      NA=10
C     N: # OF NUCLIDES IN THE CHAIN
C     A: DECAY CONSTANTS OF EACH DAUGHTER
C     W: # OF ALPHAS PER DECAYING NUCLEUS
      N=3
      A(1)=0.0037877
      A(2)=0.00043106
      A(3)=0.00058642
      W(1)= 1
      W(2)= 0
      W(3)= 1
      ST=5
C     CONSTRUCT EIGENVECTORS OF THE DECAY MATRIX
C     ***********************************************************
      CALL EIG (U,A,NA,N)
      DO201I=1,N
201   WRITE(*,899) (U(I,J),J=1,N)
C     ***********************************************************
C     CONSTRUCT TRANSFORMED WEIGHTS AND ZERO SOME ARRAYS
C     ***********************************************************
      DO14I=1,N-1
      DO14J=I+1,N
14    W(I)=W(I)+W(J)
      DO1 I=1,N
1     Y(I)=VPROD(U(1,I) ,1,W,1,N,XX)
      WRITE(*,898) (Y(I),I=1,N)
      C=0.0
      DO13I=1,N
      Q(I)=0.0
      W(I)=0.0
      B(I)=0.0
      DO13J=1,N
13    ZZ(I,J)=0.0
C     ***********************************************************
C     READ DATA
C     ***********************************************************
      WRITE(*,991)
      READ(*,992)F
      WRITE(*,993)
      READ(*,994)EFF
```

```
        WRITE(*,996)F
        WRITE(*,997)EFF
        M: # OF INTERVALS AND COUNT DATA
        WRITE(*,902)
        READ (*,904)M
        WRITE (*,906) M
        OPEN(7,FILE=FNAME,ACCESS='SEQUENTIAL',STATUS='OLD')
        READ(7,903,END=40)(YY(I),I=1,M)
  40    CONTINUE
        CLOSE(7,STATUS='KEEP')
C       TN: TIME OF START OF COUNTING FROM SAMPLE COLLECTION
        WRITE (*,935)
        WRITE (*,945)
        WRITE (*,955)
        READ (*,960) TN,DT
        WRITE (*,965) TN,DT
        WRITE (*,975)
C       VALUES OF "T" AND "D" NOW ENTERING
C       T: TIME AT END OF COLLECTION OF "D" COUNTS
C       D: COUNTS ACCUMULATED IN EACH INTERVAL
C
        T=TN
        WRITE(*,976)
        DO3 K=1,M
        T=T+DT
        WRITE(*,985)K
        D=YY(K)
        WRITE(*,995)T,D
C       CONSTRUCT  "DECAYED WEIGHT VECTOR"
        DO4 I=1,N
  4     Z(I)=(EXP(-TN*A(I))-EXP(-T*A(I)))*Y(I)
        TN=T
C       ACCUMULATE RIGHT-HAND-SIDE AND COEFFICIENT MATRIX
        C=C+D*D
        WRITE(*,921)C
        DO5 I=1,N
        B(I)=B(I)+D*Z(I)
        W(I)=B(I)
        DO5 J=1,N
  5     ZZ(I,J)=ZZ(I,J)+Z(I)*Z(J)
  3     CONTINUE
        WRITE(*,924)
        DO10I=1,N
  10    WRITE(*,925)(ZZ(I,J),J=1,N),B(I)
C       SOLVE FOR INTERMEDIATE VECTOR
        DO20I=1,N
        DA(I)=0.0
        DO20J=1,N
  20    CC(I,J)=-U(J,I)
        CALL QUAD(B,ZZ,CC,DA,Q,UU,N,N,NA,LC,TQ)
```

```
C       **********************************************************
C                   COMPUTE SENSITIVITY
C       **********************************************************
        C=0.5*(C-VPROD (W,1,Q,1,N,XX))
        WRITE(*,922)C
C       FINISH INVERSE OF ZZ
        ZZ(1,1)=1./ZZ(1,2)
        DO 11 J = 2,N
        ZZ(J,J)=1./ZZ(J,J+1)
        DO 11 I= J-1,1,-1
   11   ZZ (J,I)=-VPROD(ZZ(I,J+1),-NA,ZZ(J,J),-NA,J-I,XX)*ZZ(I,I)
        NP=N+1
        DO 12 J=1,N
        DO 12 I=J,N
        ZZ(I,J)=C*VPROD(ZZ(I,J),1,ZZ(I,I),1,NP-I,XX)
   12   ZZ(J,I)=ZZ(I,J)
C       **********************************************************
C             UNFOLD INTERMEDIATE VECTOR TO FINAL SOLUTION
C       **********************************************************
        DO6 I=1,N
        X=0.0
        DO7 J=1,N
    7   X=X+U(I,J)*Q(J)
        Z(I)=X
        AL(I)=Z(I)/(F*EFF*ST)
        P(I)=(AL(I)*A(I))/0.037
    6   CONTINUE
C       PRINT RESULTS
        WRITE(*,920)
        WRITE(*,930)N,(Z(I),I=1,N)
        WRITE(*,960)
        WRITE(*,970)N,(AL(I),I=1,N)
        WRITE(*,980)
        WRITE(*,970)N,(P(I),I=1,N)
        WRITE(*,940)
        DO 2 I=1,N
    2   WRITE(*,950) (ZZ(I,J),J=1,I)
        STOP
   99   FORMAT(I5/(2F15.5))
   98   FORMAT(I5,F10.0)
   97   FORMAT(2F10.0)
  899   FORMAT(1H ,'U = ', G14.7)
  898   FORMAT(1H ,'Y = ', G14.7)
  900   FORMAT(2F5.0)
  903   FORMAT(10F6.0)
  991   FORMAT(1H ,'ENTER FLOW RATE IN LITER/MIN IN F5.0 FORMAT')
  992   FORMAT(F5.0)
  993   FORMAT(1H ,'ENTER THE PRODUCT OF DETECTOR AND FILTER EFF')
  994   FORMAT(F4.3)
  996   FORMAT(1H ,'FLOW =',F5.0)
```

```
997   FORMAT(1H ,'EFFECTIVE EFFICIENCY =',F4.3)
902   FORMAT(1H,'ENTER"M", NO OF DATA IN "I4" FORMAT'/)
904   FORMAT(I4)
990   FORMAT(F7.0)
906   FORMAT(1H ,'M=',I5)
935   FORMAT(1H ,'ENTER   TN,  DT  IN  "2F5.0" FORMAT')
945   FORMAT(1H ,'  TN= TIME FROM END OF SAMPLING TO START OF COUNTING')
955   FORMAT(1H ,'  DT= COUNTING TIME PER MEASUREMENT IN SECONDS')
965   FORMAT(1H ,' TN,DT= ',2F9.0)
975   FORMAT(1H ,' VALUES OF "T" AND "D" NOW ENTERING')
976   FORMAT(1H ,' ENTER JUST D, COUNTS AT TIME T, IN FREE FORMAT')
985   FORMAT(1H ,' TIME AND COUNT SET,#---',I4)
995   FORMAT(1H ,' T,D = ',2F9.0)
924   FORMAT(1H ,'ZZ - MATRIX, B - VECTOR' )
925   FORMAT(//2G14.7)
921   FORMAT(1H ,'C = ',F14.0)
922   FORMAT(F14.6)
920   FORMAT(1H ,'NUMBER OF ATOMS OF EACH RADIONUCLIDE')
930   FORMAT(//I4/(6F12.0))
960   FORMAT(1H ,'CONCENTRATION IN ATOMS/LITER')
970   FORMAT(//I4/(6F12.4))
980   FORMAT(1H ,'CONCENTRATION IN PCI/LITER')
940   FORMAT(1H ,' MEAN SQ. ERROR MATRIX')
950   FORMAT(2X,1P6E13.4)
      END
      SUBROUTINE EIG(U,A,NA,N)
C     CONSTUCTS THE EIGENVECTORS OF THE COUPLED-DECAY MATRIX
      DIMENSION U(NA,NA),A(NA)
C     ZEROING THE ARRAY
      DO1 I=1,N
      DO1 J=1,N
 1    U(I,J)=0.0
C     STEPPING THROUGH THE COLUMNS (EIGENVECTORS)
      DO2 J=1,N
C     FILLING THE BOTTOM PART OF THE VECTOR
      DO3 I=J,N
      X=1.0
      IM=I-1
      IF (IM-J) 6,7,7
 7    DO4 K=J,IM
 4    X=X*A(K)
 6    IP=I+1
      IF  (N-IP)3,8,8
 8    DO5  K=IP,N
 5    X=X*(A(K)-A(J))
 3    U(I,J)=X
 2    CONTINUE
C     NORMALIZE VECTORS
      DO9J=1,N
      X=0.
```

```
      DO10I=1,N
 10   X=X+U(I,J)**2
      X=1./SQRT(X)
      DO9I=1,N
  9   U(I,J)=X*U(I,J)
      RETURN
      END
      SUBROUTINE QUAD(A,B,C,D,X,U,NX,NC,NB,LC,TN)
      DIMENSION A(1),B(NB,1),C(NB,1),D(1),X(1),U(1),LC(1),TN(1)
      NP=NC+1
C     REDUCE THE PROBLEM TO "NORMAL" FORM
      CALL MCDCMP(B,NB,NX,X)
      DO1 I=1,NX
      C(I,NP)=A(I)
      DO2J=1,I
  2   B(J,I+1)=B(I,J)
      DO3J=1,NP
  3   C(I,J)=(C(I,J)-VPROD(B(I,1),NB,C(1,J),1,I-1,XX))/B(I,I)
  1   CONTINUE
      DO7J=1,NC
      LC(J)=J
      U(J)=0.0
      XX=1./SQRT(VPROD(C(1,J),1,C(1,J),1,NX,XX))
      DO9I=1,NX
  9   C(I,J)=XX*C(I,J)
      D(J)=XX*T(J)-VPROD(C(1,J),1,C(1,NP),1,NX,XY)
      TN(J)=XX
  7   CONTINUE
      NP=1
      NI=0
C     MAIN ITERATION
 10   DO41=1,NX
  4   X(I)= VPROD(C(I,1),NX,U,1,NI,XY)
C     PREPARE FOR LM COMPUTATION
      DO28I=1,NI
 28   U(I)=(D(I)-VPROD(B(I,1),NB,U,1,I-1,XY))/B(I,1)
C     CHECK VIOLATIONS; FIND ONE MOST NEGATIVE LM
      XX=0.0
      K=0
      DO5J=NP,NC
      XY=VPROD(C(1,J),1,X,1,NX,XY)-D(J)
      IF(XY)5,5,6
  6   IF(NP-NX)38,38,40
 40   STOP
 38   IF(NI)36,36,37
 37   DO13I=1,NI
 13   A(I)=(VPROD(C(1,I),1,C(1,J),1,NX,XY)-
     1       VPROD(A,1,B(I,1),NB,I-1,XY))/B(I,I)
 36   A(NP)=VPROD(C(1,J),1,C(1,J),1,NX,XY)-VPROD(A,1,A,1,NI,XY)
      XU=(D(J)-VPROD(A,1,U,1,NI,XY))/A(NP)
```

```
 27    B(I,J)=(VPROD(C(1,I),1,C(1,J),1,NX,XY)-
      1          VPROD(B(1,I),NB,B(J,1),NB,J-1,XY))/B(J,J)
       B(I,I)=SQRT(VPROD(C(1,I),1,C(1,I),1,NX,XY)-
      1          VPROD(B(I,1),NB,B(I,1),NB,IM,XY))
 26    U(I)=(D(I)-VPROD(B(I,1),NB,U,1,IM,XY))/B(I,I)
       U(NI)=U(NI)/B(NI,NI)
       GO TO 29
 17    DO23J=1,NX
       I=NX+1-J
 23    X(I)=(X(I)+C(I,NC+1)-VPROD(B(I,I+2),NB,X(I+1),1,J-1,XY))/B(I,I+1)
       IF(NI.EQ.0)GOTO30
       DO12I=1,NI
       J=NI+1-I
 12    U(J)=(U(J)-VPROD(B(J+1,J),1,U(J+1),1,I-1,XY))/B(J,J)
       DO39I=1,NC
 39    U(I)=TN(LC(I))*U(I)
 30    IF(NP.GT.NC)GOTO32
       DO31J=NP,NC
 31    U(J)=0.0
 32    DO33I=1,NC-1
       XX=U(I)
       DO34J=1,NC
       IF(LC(J)-I)34,35,34
 34    CONTINUE
 35    U(I)=U(J)
       U(J)=XX
       K=LC(I)
       LC(I)=LC(J)
       LC(J)=K
 33    CONTINUE
       RETURN
       END
       FUNCTION VPROD(A,L,B,M,N,X)
       DIMENSION A(1),B(1)
       DOUBLE PRECISION XX
       XX=0.0
       IF(N)1,1,2
  2    I=1-L
       J=1-M
       DO3K=1,N
       I=I+L
       J=J+M
  3    XX=XX+DBLE(A(I))*DBLE(B(J))
  1    X=XX
       VPROD=XX
       RETURN
       END
       SUBROUTINE MCDCMP(A,L,N,X)
       DIMENSION A(L,1),X(1)
       IF(N)3,3,4
```

```
        IF(XX-XU)5,5,16
  16    K=J
        XX=XU
        A(NP)=SQRT(A(NP))
        DO19I=1,NP
  19    B(NP,I)=A(I)
   5    CONTINUE
        IF(K)18,17,18
C       IF WE HAVE ONE, COMPUTE THE LM'S
  18    NI=NP
        NP=NP+1
        I=LC(NI)
        LC(NI)=LC(K)
        LC(K)=I
        XU=D(NI)
        D(NI)=D(K)
        D(K)=XU
        DO20I=1,NX
        XU=C(I,NI)
        C(I,NI)=C(I,K)
  20    C(I,K)=XU
        U(NI)=XX
  29    XX=0.0
        K=0
        IF(NI.EQ.1)GOTO10
        DO21I=1,NI-1
        J=NI-I
        U(J)=(U(J)-VPROD(B(J+1,J),1,U(J+1),1,I,XY))/B(J,J)
        IF(XX-U(J))22,21,21
  22    XX=U(J)
        K=J
  21    CONTINUE
        IF(K)24,10,24
C       IF AN LM>0 THEN DELETE THE CONSTRAINT
  24    NP=NI
        NI=NI-1
        XX=D(NP)
        D(NP)=D(K)
        D(K)=XX
        I=LC(NP)
        LC(NP)=LC(K)
        LC(K)=I
        DO25I=1,NX
        XX=C(I,NP)
        C(I,NP)=C(I,K)
  25    C(I,K)=XX
C       THEN DO THE REDUCTION FROM K ON
        DO26I=K,NI
        IM=I-1
        IF(IM)26,26,8
   8    DO27J=1,IM
```

```
4      DO1J=1,N
       JM=J-1
       A(J,J)=SQRT(A(J,J)-VPROD(A(J,1),L,A(J,1),L,JM,Z))
       X(J)=1./A(J,J)
       IF(J.EQ.N)GOTO1
       JP=J+1
       DO2I=JP,N
2      A(I,J)=(A(I,J)-VPROD(A(I,1),L,A(J,1),L,JM,Z))*X(J)
1      CONTINUE
3      RETURN
       END

A:
```

This appendix presents in tabular form the results of the daughter concentrations calculated using both methods of analysis. The tables are listed by the category of runs described in Chapter V. As can be seen in the following tables, all values except for the concentration of Ra-A are in agreement between the two methods. The values of Ra-A in all cases is off by a factor of 2, which indicates a program error. It is recommended that further work on the program be made to determine the source of this error and also to determine sensitivity of using the least square method.

TABLE VIII

Comparison of Values With Blower Only

Tsivoglou			Weighted Least Square		
RUN 1					
Ra-A	Ra-B	Ra-C	Ra-A	Ra-B	Ra-C
9.59	6.39	2.54	4.57	5.33	3.76
8.38	4.52	2.34	3.90	4.10	3.33
4.61	2.76	2.22	2.67	2.73	2.39
4.96	1.79	0.87	2.98	1.88	1.00
0.17	0.19	2.94	2.48	1.53	1.30
3.12	0.89	0.35	1.99	1.02	0.39
2.50	1.05	0.41	1.71	1.05	0.47
2.86	1.02	0.46	1.59	0.95	0.66
RUN 2					
6.73	4.34	2.86	3.67	4.33	3.02
5.94	2.80	2.05	3.30	2.91	2.27
3.53	2.09	1.90	2.05	2.09	1.99
2.76	0.95	0.71	1.72	1.03	0.76
4.41	1.58	0.30	2.63	1.64	0.48
3.86	1.11	0.64	2.54	1.72	0.71
3.64	1.24	0.65	2.14	1.30	0.79

TABLE IX

Comparison of Values With EAC in Operation

Taivoglou				Weighted Least Square		
RUN 1						
Ra-A	Ra-B	Ra-C		Ra-A	Ra-B	Ra-C
5.27	4.45	2.94		2.70	3.87	3.49
5.52	4.08	2.86		3.41	4.01	3.05
1.95	0.11	0.14		1.30	0.28	0.11
1.57	0.04	0.24		1.09	0.27	0.17
2.43	0.40	0.00		1.38	0.39	0.02
2.06	0.11	0.26		1.02	0.11	0.38
2.74	0.34	0.00		1.26	0.25	0.10
2.66	0.24	0.00		1.52	0.29	0.02
1.08	0.53	4.01		3.47	3.25	1.97
6.85	3.64	2.15		3.54	3.62	2.57
RUN 2						
7.14	4.59	2.16		3.70	4.04	2.83
1.80	0.72	0.13		0.97	0.17	0.17
1.91	0.22	0.21		0.91	0.21	0.33
2.03	0.35	0.03		1.43	0.42	0.05
2.84	0.17	0.00		1.70	0.31	0.00
2.38	0.15	0.03		1.53	0.33	0.02
2.36	0.23	0.03		1.21	0.21	0.19
7.11	2.42	0.61		3.77	2.65	0.93
RUN 3						
7.32	3.92	3.75		3.95	3.99	3.03
5.27	3.84	2.94		2.84	3.68	3.21
2.19	0.22	0.02		1.19	0.24	0.11
2.21	0.14	0.03		1.36	0.24	0.08
2.32	0.16	0.00		1.17	0.13	0.34
2.47	0.18	0.15		1.53	0.29	0.65
2.70	0.24	0.00		1.78	0.33	0.00
2.98	0.28	0.00		1.50	0.35	0.03
2.76	0.27	0.00		1.69	0.35	0.02
RUN 4						
2.21	0.09	0.06		1.36	0.23	0.08
2.43	0.15	0.06		1.66	0.35	0.01
0.99	0.00	0.51		1.21	0.24	0.11
2.47	0.15	0.02		1.49	0.23	0.05
2.56	0.29	0.00		1.38	0.37	0.02
2.13	0.10	0.05		1.28	0.21	0.07

TABLE X

Comparison With Half of Intake Sealed on the EAC

Tsivoglou			Weighted Least Square		
RUN 1					
Ra-A	Ra-B	Ra-C	Ra-A	Ra-B	Ra-C
4.64	2.72	2.18	3.18	2.96	2.11
2.24	0.32	0.00	1.37	0.45	0.00
2.55	0.18	0.00	1.52	0.26	0.01
2.23	0.18	0.14	1.49	0.37	0.10
2.48	0.25	0.00	1.36	0.27	0.10
1.85	0.10	0.12	1.35	0.33	0.04
2.42	0.17	0.00	1.46	0.25	0.02
6.12	2.09	0.67	4.92	3.58	0.00
5.75	3.50	2.02	3.94	3.59	2.11
RUN 2					
12.33	6.78	2.99	5.19	5.90	4.72
3.83	1.63	0.86	2.13	1.53	1.13
3.03	0.16	0.10	2.22	0.47	0.03
4.04	0.39	0.00	2.08	0.54	0.00
1.97	0.09	0.16	1.40	0.32	0.07
1.89	0.07	0.09	1.17	0.17	0.08
2.54	0.21	0.00	1.25	0.21	0.04
5.78	0.67	0.06	3.33	0.87	0.21
5.68	2.99	1.25	3.08	2.87	2.12
RUN 3					
6.28	3.95	2.21	2.75	3.43	2.88
2.25	1.00	0.53	1.62	1.44	0.45
2.50	0.03	0.02	1.28	0.23	0.00
2.60	0.26	0.00	1.21	0.21	0.09
2.53	0.24	0.00	1.52	0.36	0.02
2.33	0.23	0.00	1.66	0.36	0.00
2.40	0.19	0.01	1.61	0.35	0.00
5.87	0.98	0.00	3.42	1.14	0.14
8.21	3.41	0.81	4.59	3.71	1.18

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The effectiveness of using an electrostatic precipitator as a means
for reducing harmful levels of radon progeny in the home was evaluated.
A commercially available precipitator, manufactured by the Honeywell
Corporation, was used during the course of this study. The specific
model used was the Honeywell Electronic Air Cleaner model number F50A1009.

Daughter concentrations were measured by the modified Tsivoglou
method. Samples were collected on a 2-inch millipore filter and alpha
emissions were measured with a ZnS(Ag) scintillator. A sample collection
time of 5 minutes was used. Sample counting intervals of 2-5, 6-20, and
21-30 minutes after sample collection were used.

During this study air samples were made using the blower fan and
filters alone with no power to the electrostatic precipitator, and with
the electrostatic precipitator energized. The reduction in the working
level as a result of using the blower fans and filters only was 75 percent.
With the electrostatic precipitator energized the reduction level rose to
90 percent. It is therefore concluded that the electrostatic precipitator
is an effective means for reducing radon progeny concentrations in the
home. Originator Supplied keywords
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